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OPTIMIZING ENERGY HUB SYSTEM OPERATION WITH ELECTRICAL AND THERMAL DEMAND RESPONSE PROGRAMS

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Highlights

- The study focuses on EH optimization, including renewable energy systems, combined heat and power, and more, to minimize costs.
- Demand response programs (DRP) play a crucial role in adjusting electricity consumption in response to price fluctuations.
- The article incorporates Electrical Demand Response Program (EDRP) and Thermal Demand Response Program (TDRP) into the EH.
- The optimization problem is addressed through Mixed Integer Linear Programming (MILP) and CPLEX solver in GAMS.
- The effectiveness of the model is validated by comparing results from various case studies.

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ABSTRACT: Electricity consumption is increasing rapidly and many countries are looking for ways to cope with the energy crisis. Morever, the world is facing the problem of global warming caused by emissions. Therefore, it is of great importance to operate power systems efficiently. Energy Hub (EH) represents a versatile energy system capable of providing efficient and optimal solutions for the operation of power systems across multiple carriers. This paper examines the optimization of an EH encompassing renewable energy systems (RES) like wind and photovoltaic, combined heat and power (CHP), transformer, absorption chiller, energy storage system (ESS) and furnace with aiming at minimizing the cost. Demand response is an energy sector strategy that entails modifying electricity consumption patterns in reaction to fluctuations in electricity supply or pricing. The objective of demand response programs (DRP) is to curtail or shift electricity consumption during periods of elevated electricity prices. Therefore, Electrical Demand Response Program (EDRP) for electrical demand and the Thermal Demand Response Program (TDRP) for heating demand are incorporated into the EH. The optimization problem is formulated as Mixed Integer Linear Programming (MILP) and solved with CPLEX solver in GAMS. The outcomes of various case studies are compared to ascertain the model's efficiency.

Keywords: *Demand response program, Energy Hub, Optimization, Renewable energy systems*

1. INTRODUCTION

The rise in energy demand in the world is followed closely. There are reports from various organizations that the amount of electricity consumption has increased by almost four times over the last half century. When global warming, environmental problems and energy needs are evaluated together, the importance of using clean, reliable, abundant and renewable alternative energy sources is increasing. The contribution of renewable energy sources (RES) is expected to be significant in meeting global targets for reducing greenhouse gas emissions. It is foreseen that technological energy harvesting alternatives will increase and costs will decrease rapidly with technological developments. The Energy Hub (EH) is a recently developed technology that aims to optimize the operations of energy systems. EH systems use the energy sources efficiently and convert a set of different energy carriers such as electricity, heat, natural gas and so on in its input into a set of energy demands such as electricity, cooling and heating. They achieve the generation, distribution, conversion, and retention of diverse interconnected energy carriers. [1, 2]. EH reduces costs and emissions and improves the system reliability with combining RES as the distributed generation (DG) [1, 3]. The most countries are expected to use EH systems as a robust tool for the optimal planning and operation of multiple energy carriers [3].

There are many studies on EH in several aspects such as optimal modeling, scheduling, load dispatch, operation and energy management. Lu et al. [2] have developed a computational model to optimize the allocation of energy in an EH system, which includes an energy storage system (ESS) and a demand response program (DRP). The primary goal is to minimize the overall cost associated with electricity consumption. Eladl et al. [3] have proposed a model that aims to optimize the operation and configuration

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of EH in order to minimize costs, reduce emissions, and maximize profits. Rakipour and Barati [4] have developed a mixed-integer linear programming (MILP) model aimed at optimizing the operation of an EH that incorporates heating, cooling, electrical storage systems, RES and DRPs. The goal is to maximize the profitability of the EH. Tian et al. [5] have introduced a stochastic model based on risk for optimizing the operation of an EH that encompasses storage systems, a wind energy system (WES), the electricity and heating markets and DRP, all with the objective of cost minimization. Additionally, they have incorporated downside risk constraints (DRC) to mitigate the uncertainties and associated risks. Nasir et al. [6] have investigated the day-ahead scheduling of an electric-hydrogen integrated energy system, considering various components such as wind and photovoltaic energy systems, electric storage, thermal storage, hydrogen storage systems, combined heat and power (CHP), biomass units, boilers, solar heaters and hydrogen electrolyzer. The main objective is to optimize the operational cost of the system while establishing connections with demand response aggregators. Davatgaran et al. [7] have proposed a model aimed at determining the most efficient bidding strategy for an EH's involvement in the day-ahead market, with the main goal of reducing costs. Vahid-Pekdel et al. [8] have proposed a comprehensive model for the optimal operation of an EH. The model incorporates various components such as WES, storage systems, DRPs and participation in energy markets. The main objective of this model is to minimize the operational costs associated with operating the EH while ensuring efficient utilization of resources. Shahrabi et al. [9] have presented a model for the strategic planning and optimal operation of an EH system, which addresses both electrical and thermal demands to minimize the overall cost. Cao et al. [10] have proposed a multi-energy hub system model that focuses on minimizing carbon emissions and operational expenses. The study has also integrated real-time DRPs, resulting in cost and emission reductions. Jamalzadeh et al. [11] have proposed a MILP model for an EH. Their objective is to minimize costs while considering the thermal energy market and incorporating both thermal and electrical DRPs. Dolatabadi and Mohammadi-Ivatloo [12] have presented a smart EH scheduling model under DRP. They have also integrated the conditional value-at-risk (CVaR) method into the model for risk measurement. Pazouki et al. [13] have proposed a model for optimal operation of the EH with consideration of cost, emission and reliability. Pazouki and Haghiham [14] have proposed a mathematical formulation including costs related to operation, emission, reliability and investment of the EH for optimal planning. Thang et al. [15] have presented a stochastic scheduling framework aiming to minimize the cost and emission for multi EH systems. Majidi et al. [16] have presented a model considering both economy and environment for operation of the EH in the presence of DRP.

The use of RES is a promising way to decrease emission and cost and increase reliability. Therefore, in this paper, the proposed EH system includes wind and PV energy systems from RES. Demand Response Programs (DRP) are valuable tools that facilitate efficient load shifting for the management of EH system to minimize cost. The Electrical Demand Response Program (EDRP) for electrical demand and the Thermal Demand Response Program (TDRP) for heating demand are included in the system. The other components of the EH system are transformer, CHP, furnace, absorption chiller and ESS. The study makes a significant contribution to addressing the contemporary challenges associated with the escalating electricity consumption and the global energy crisis. In light of the pressing issue of global warming attributed to emissions, the study emphasizes the critical importance of enhancing the efficiency of power systems. It introduces the concept of an EH as a versatile energy system with incorporating RES such as wind and solar, as well as energy storage technology to efficiently meet the demands for electricity, heating and cooling and with incorporating DRPs to provide a strategic approach to changing electricity consumption patterns in response to changes in supply or pricing. The optimization problem with the aim of minimizing the cost of EH with consideration of EDRP and TDRP in three case studies have been analyzed. The problem is solved using CPLEX solver in GAMS software.

2. THE STRUCTURE OF THE ENERGY HUB SYSTEM

The EH proposed in this study incorporates various components that are specifically designed to generate, convert, and store different forms of energy. These components allow for the harnessing and storage of energy to meet the required demands efficiently. The EH system is powered by a combination of natural gas, electricity from the external grid and RES such as wind and solar. The output of the system includes energy needs for electricity, heating, and cooling. The presented EH contains a wind energy system (WES), a photovoltaic energy system (PVES), a furnace, a CHP, a transformer, an ESS, an absorption chiller, an EDRP unit and a TDRP unit. Figure 1 illustrates the schematic diagram of the proposed model for the EH system.

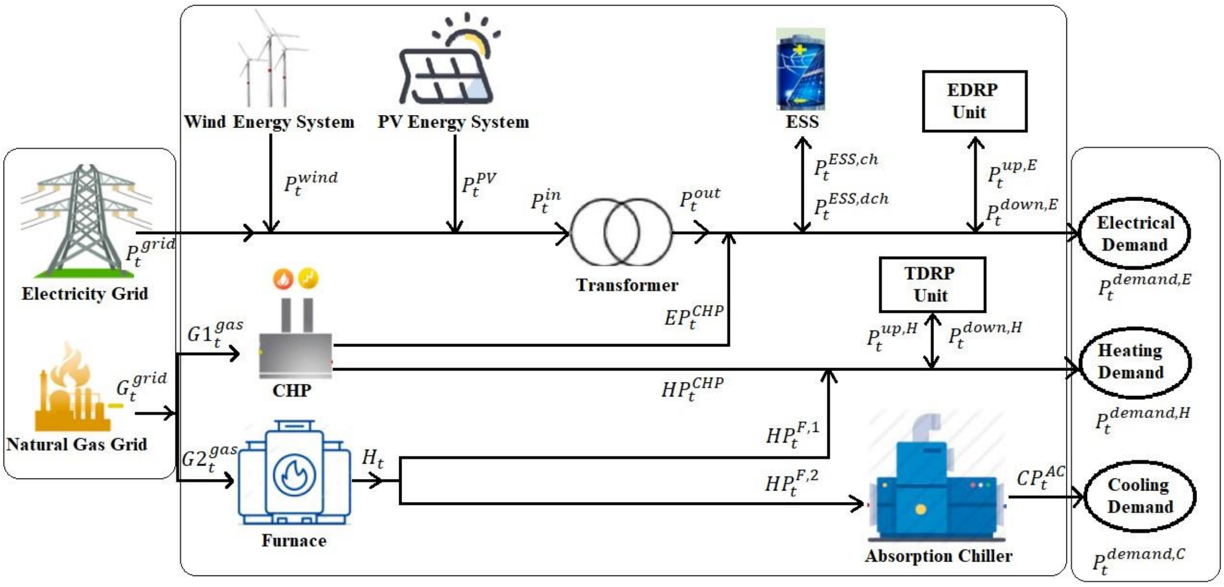

Figure 1. The suggested EH system

The electricity demand within the described system is met through a combination of solar and wind systems, the CHP unit and the main grid. The heating demand is fulfilled by both the CHP unit and the furnace, while cooling needs are catered for by an absorption chiller. The wind and solar energy systems generate environmentally friendly energy. The CHP utilizes natural gas to generate both heat and electricity. The absorption chiller takes the heat and converts it into cooling demand. The furnace uses natural gas to meet heating demand. The transformer is used to adjust the voltage levels of electricity. The ESS is also incorporated within the system to charge and discharge electricity as required.

3. MATHEMATICAL FRAMEWORK FOR THE PROPOSED PROBLEM FORMULATION

Here, a comprehensive explanation of the mathematical portrayal of the components in the EH are provided. Additionally, the objective function and constraints pertaining to this problem are elaborated.

3.1. Wind Energy System Modeling

The electricity generated by a WES depends on numerous factors, such as wind speed, the number and characteristics of turbines in the system. This calculation can be expressed using Equation 1 [17,18,19].

$$P_t^{wind} = N^{WT} \times \begin{cases} P_{rated}^{wind}, \quad v_{rated}^{wind} < v_t^{wind} < v_{out}^{wind} \\ 0, \quad v_t^{wind} < v_{in}^{wind} \ or \ v_t^{wind} > v_{out}^{wind} \\ P_{rated}^{wind} x \left(\frac{v_t^{wind} - v_{in}^{wind}}{v_{rated}^{wind} - v_{in}^{wind}} \right)^3, \quad v_{in}^{wind} < v_t^{wind} < v_{rated}^{wind} \end{cases} \tag{1}$$

where P_t^{wind} is the output power of the WES at hour t, N^{WT} is the number of wind turbines, P_{rated}^{wind} is the rated power of the wind turbine (MW), v_t^{wind} is the wind speed in the region at hour t (m/s), v_{out}^{wind},

v_{in}^{wind} and v_{rated}^{wind} are the cut-out, cut-in and rated wind speeds (m/s) that are specific values for the wind turbine.

3.2. Photovoltaic Energy System Modeling

The electricity generated by a PVES is dependent on numerous factors including the temperature and sunlight intensity of the surroundings, as well as the number and specifications of the PV panels used in the system. This calculation can be expressed using Equations 2a-2e [3, 20].

$$P_t^{PV} = N^{PV} \times FF^{PV} \times V_t^{PV} \times I_t^{PV} \tag{2a}$$

$$FF^{PV} = \frac{V_{MPP}^{PV} \times I_{MPP}^{PV}}{V_{OC}^{PV} \times I_{SC}^{PV}} \tag{2b}$$

$$V_t^{PV} = V_{OC}^{PV} - C_{VT}^{PV} \times T_t^C \tag{2c}$$

$$I_t^{PV} = S_t \times [I_{SC}^{PV} + C_{CT}^{PV} \times (T_t^C - 25)] \tag{2d}$$

$$T_t^C = T_t^A + S_t \times \left(\frac{T^B - 20}{0.8}\right) \tag{2e}$$

where P_t^{PV} is the power output of the PVES at hour t, N^{PV} is the number of PV panels within the system, FF^{PV} is the filling factor of the panel, V_t^{PV} and I_t^{PV} are the voltage and current characteristic of the panel at hour t, respectively, V_{MPP}^{PV} and I_{MPP}^{PV} denote the maximum power point voltage and current, respectively, V_{OC}^{PV} and I_{SC}^{PV} are the open circuit voltage and short circuit current of the panel, respectively, C_{VT}^{PV} and C_{CT}^{PV} represent the voltage and current temperature coefficient of the panel, respectively, T_t^A and T_t^C are the temperature of the ambient and panel at hour t, respectively, S_t is the solar radiation level at hour t, T^B indicates the nominal operating temperature of the panel.

3.3. Combined Heat and Power Modeling

The CHP system receives the natural gas and converts it into electricity, by considering the efficiency of converting gas to electricity as shown in Equation 3a, as well as into heat, considering the efficiency of converting gas to heat as shown in Equation 3b [4].

$$EP_t^{CHP} = \eta_{GE}^{CHP} \times G1_t^{gas} \tag{3a}$$

$$HP_t^{CHP} = \eta_{GH}^{CHP} \times G1_t^{gas} \tag{3b}$$

where EP_t^{CHP} is the output electrical power of the CHP system at hour t, η_{GE}^{CHP} is the efficiency for gas to electricity conversion for CHP, $G1_t^{gas}$ is the input of natural gas to the CHP at hour t, HP_t^{CHP} is the output heat power of the CHP system at hour t, η_{GH}^{CHP} is the efficiency for gas to heat conversion for CHP.

3.4. Furnace Modeling

The heat output of the furnace in the EH is determined by assessing the natural gas input and its conversion efficiency. This calculation, detailed in Equation 4, mathematically represents the heat power generated.

$$H_t = HP_t^{F,1} + HP_t^{F,2} = \eta_{GH}^{F} \times G2_t^{gas} \tag{4}$$

where H_t is the output heat power of the furnace at hour t, η_{GH}^{F} is the efficiency of natural gas to heat power conversion for the furnace, $G2_t^{gas}$ is the input of the natural gas to the furnace at hour t. A portion of H_t is used to meet the heating demand that is represented as $HP_t^{F,1}$, while another portion is utilized as input for the absorption chiller that is represented as $HP_t^{F,2}$.

3.5. Absorption Chiller Modeling

It operates by converting heat into cooling capacity. The calculation of the cooling capacity produced by the absorption chiller is determined by the input heat power and the efficiency of the conversion process from heat to cooling, as depicted in Equation 5 [4].

$$CP_t^{AC} = \eta_{HC}^{AC} \times HP_t^{F,2} \tag{5}$$

where CP_t^{AC} is the output cooling power of the absorption chiller at hour t, η_{HC}^{AC} is the efficiency of heat to cooling conversion for the absorption chiller, $HP_t^{F,2}$ is the heat power input to absorption chiller at hour t.

3.6. Transformer Modeling

A transformer is installed in the EH for voltage transformation. The calculation of the power output from the transformer relies on both the input power provided to the transformer and its efficiency, as described in Equation 6a [4]. The input power to the transformer consists of the electrical power from grid and the output power of WES and PVES as shown in Equation 6b.

$$P_t^{out} = \eta_{EE}^{T} \times P_t^{in} \tag{6a}$$

$$P_t^{in} = P_t^{grid} + P_t^{wind} + P_t^{PV} \tag{6b}$$

where P_t^{in} is the input power of the transformer, η_{EE}^{T} is the efficiency of the transformer, P_t^{out} is the output power of the transformer, P_t^{grid} is the electrical power taken from electrical grid at hour t.

3.7. Energy Storage System Modeling

The ESS is utilitized to charge and discharge the electricity. The constraints of the ESS are given in Equations 7a-7e [2, 17].

$$SOC_t^{ESS} = SOC_{t-1}^{ESS} + (P_t^{ESS,ch} \times \eta_{ch}) - (P_t^{ESS,dch}/\eta_{dch}) \tag{7a}$$

$$P_{min}^{ESS,ch} \leq P_t^{ESS,ch} \leq P_{max}^{ESS,ch} \tag{7b}$$

$$P_{min}^{ESS,dch} \leq P_t^{ESS,dch} \leq P_{max}^{ESS,dch} \tag{7c}$$

$$SOC_{min}^{ESS} \leq SOC_t^{ESS} \leq SOC_{max}^{ESS} \tag{7d}$$

$$I_t^{ESS,ch} + I_t^{ESS,dch} \leq 1\ ,\quad I_t^{ESS,ch}\ and\ I_t^{ESS,dch}\ \in\ \{0,1\} \tag{7e}$$

where SOC_t^{ESS} is the state of charge (SoC) of the ESS at hour t, $P_t^{ESS,ch}$ is the charging power of the ESS at hour t, η_{ch} is the charging efficency of the ESS, $P_t^{ESS,dch}$ is the discharging power of the ESS at hour t, η_{dch} is the discharging efficency of the ESS, $P_{min}^{ESS,ch}$ and $P_{max}^{ESS,ch}$ are the minimum and maximum charging power of the ESS, respectively, $P_{min}^{ESS,dch}$ and $P_{max}^{ESS,dch}$ are the minimum and maximum discharging power of the ESS, respectively, SOC_{min}^{ESS} and SOC_{max}^{ESS} are the minimum and maximum capacity of SoC of the ESS at hour t. $I_t^{ESS,ch}$ and $I_t^{ESS,dch}$ represent the binary variables that show the charging and discharging situation of the ESS, respectively. The battery must be in either charging or discharging state as described in Equation 7e.

3.8. Electrical Demand Response Program Constraints

The constraints of the EDRP are given in Equations 8a-8d [2, 4].

$$\sum_{t=1}^{T} P_t^{up,E} = \sum_{t=1}^{T} P_t^{down,E} \tag{8a}$$

$$0 \leq P_t^{up,E} \leq MRT_E^{up} \cdot P_t^{demand,E} \cdot I_t^{up,E} \tag{8b}$$

$$0 \leq P_t^{down,E} \leq MRT_E^{down} \cdot P_t^{demand,E} \cdot I_t^{down,E} \tag{8c}$$

$$0 \leq I_t^{down,E} + I_t^{up,E} \leq 1 \tag{8d}$$

where $P_t^{up,E}$ and $P_t^{down,E}$ are the shipted up and shifted down electrical power demand at hour t, respectively, MRT_E^{up} and MRT_E^{down} are the maximum ratio of the shifted up and shifted down electrical power demand, $P_t^{demand,E}$ is the electrical power demand at hour t, $I_t^{up,E}$ and $I_t^{down,E}$ are the binary variables that show the shifting up and shifting down situation of electrical demand at hour t, respectively.

Equation 8a provides the balance between shifted up and shifted down electrical demands. Equation 8b and 8c express the limits for allowed shifted up and shifted down electrical power demands with respect to the maximum ratio of related electrical power demand, respectively. Equation 8d prevents to shift up and shift down the electrical power demand at the same time.

3.9. Thermal Demand Response Program Constraints

The constraints of the TDRP are given in Equations 9a-9d [2].

$$\sum_{t=1}^{T} P_t^{up,H} = \sum_{t=1}^{T} P_t^{down,H} \tag{9a}$$

$$0 \leq P_t^{up,H} \leq MRT_H^{up} \cdot P_t^{demand,H} \cdot I_t^{up,H} \tag{9b}$$

$$0 \leq P_t^{down,H} \leq MRT_H^{down} \cdot P_t^{demand,H} \cdot I_t^{down,H} \tag{9c}$$

$$0 \leq I_t^{down,H} + I_t^{up,H} \leq 1 \tag{9d}$$

where $P_t^{up,H}$ and $P_t^{down,H}$ are the shipted up and shifted down heating power demand at hour t, respectively, MRT_H^{up} and MRT_H^{down} are the maximum ratio of the shifted up and shifted down heating power demand, $P_t^{demand,H}$ is the heating power demand at hour t, $I_t^{up,E}$ and $I_t^{down,E}$ are the binary variables that show the shifting up and shifting down situation of heat demand at hour t, respectively.

Equation 9a provides the balance between shifted up and shifted down heat demands. Equation 9b and 9c express the limits for allowed shifted up and shifted down heating power demands with respect to the maximum ratio of related heat demand, respectively. Equation 9d prevents to shift up and shift down the heating power demand at the same time.

3.10. Objective Function

The main objective of the problem is to minimize the overall cost. This total cost is determined by considering both the amount and price of electricity and natural gas, as described in Equation 10.

$$Cost = \sum_{t=1}^{T} \lambda_t^{el} \times P_t^{grid} + \lambda_t^{ng} \times G_t^{grid} \ \ where \ \ G_t^{grid} = G1_t^{gas} + G2_t^{gas} \tag{10}$$

where λ_t^{el} is the price of electricity from electrical grid at hour t, λ_t^{ng} is the price of natural gas from natural gas grid at hour t and G_t^{grid} is the natural gas taken from naural gas grid at hour t. G_t^{grid} is utilitized for both input to CHP ($G1_t^{gas}$) and input to furnace ($G2_t^{gas}$).

3.11. Energy Balance Constraints

Equations 11a, 11b, and 11c represent the energy equilibrium between power generation and consumption in terms of electricity, heating, and cooling requirements.

$$P_t^{demand,E} = P_t^{out} + P_t^{ESS,dch} - P_t^{ESS,ch} + EP_t^{CHP} + P_t^{down,E} - P_t^{up,E} \tag{11a}$$

$$P_t^{demand,H} = HP_t^{CHP} + HP_t^{F,1} + P_t^{down,H} - P_t^{up,H} \tag{11b}$$

$$P_t^{demand,C} = CP_t^{AC} \tag{11c}$$

where $P_t^{demand,E}$ is the electrical demand at hour t, $P_t^{demand,H}$ is the heating demand at hour t and $P_t^{demand,C}$ is the cooling demand at hour t.

Equation 11a gives the energy balance for the electrical demand. The sum of the output power of the transformer that receives the electrical power from grid and the output power of WES and PVES as an input, the discharging power of the ESS, the output electrical power of the CHP system and shifted down electrical power demand at hour t must be equal to the sum of electrical demand, the charging power of the ESS and shifted up electrical power demand at hour t.

Equation 11b gives the energy balance for the heating demand. The sum of the output heat power of the CHP system, the heat power generated by the furnace and not used in the absorption chiller and shifted down heating power demand at hour t must be equal to the sum of heating demand and shifted up heating power demand at hour t.

Equation 11c gives the energy balance for the cooling demand. The cooling requirement during hour t should be satisfied by the absorption chiller's cooling capacity during that same hour.

4. CASE STUDIES AND RESULTS

4.1. Input Data

The parameter values of the WES are taken from the study [21]. There are 50 wind turbines in the WES. The parameter values of PVES are taken from the study [22]. There are 100 PV panels in the PVES. The data regarding wind speed, solar radiation, and ambient temperature have been taken from meteorological sources. The parameter values of the CHP [4], the absorption chiller [4], the furnace [23], the transformer [23], the ESS [23], the maximum ratios of shifted electrical and heat demand, both upwards and downwards [5], are provided in Table 1.

Table 1. The parameter values

Parameter	Value	Parameter	Value	Parameter	Value
η_{GE}^{CHP}	0.40	η_{ch}	0.90	MRT_E^{up}	0.20
η_{GH}^{CHP}	0.35	η_{dch}	0.90	MRT_E^{down}	0.20
η_{HC}^{AC}	0.92	SOC_{min}^{ESS}	120	MRT_H^{up}	0.20
η_{GH}^{F}	0.90	SOC_{max}^{ESS}	600	MRT_H^{down}	0.20
η_{EE}^{T}	0.98	$SOC\ (t=0)$	120		

Figure 2 displays the data pertaining to the electricity, heating, and cooling requirements, while Figure 3 illustrates the hourly rates for electrical energy. The natural gas price is fixed for each hour and taken as 12 $/MWh [23].

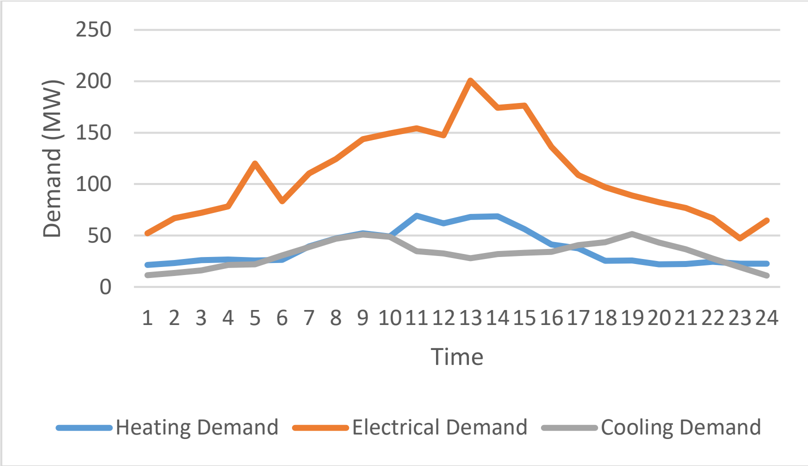

Figure 2. The electrical, heating and cooling demand

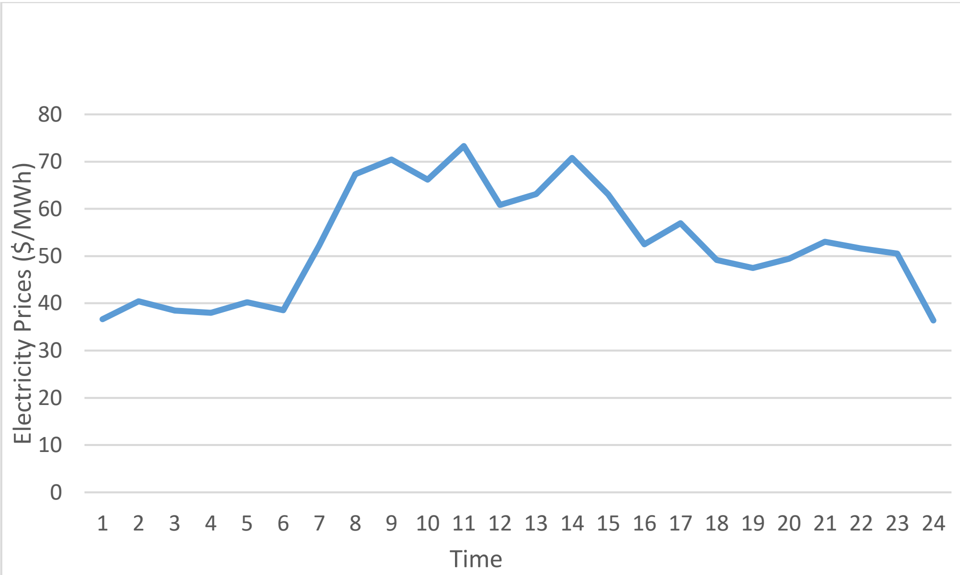

Figure 3. The electrical energy prices

4.2. Case Studies

The optimal operation of the EH is investigated for three different cases:

Case 1: Both EDRP and TDRP are not considered.
Case 2: EDRP is considered and TDRP is not considered.
Case 3: Both EDRP and TDRP are considered.

The proposed optimization is formulated as MILP and solved under GAMS software using CPLEX solver. GAMS serves as a robust tool for modeling a spectrum of optimization problems, encompassing linear, nonlinear, and combinatorial scenarios [24]. It provides a range of solvers that are designed to handle optimization problems based on mathematical programming. One such solver is CPLEX, known for its advanced capabilities in solving complex optimization problems [4]. The CPLEX solver is widely recognized as a powerful and efficient tool that enhances the optimization capabilities of GAMS software. This robust solver excels in determining optimal values for complex optimization problems, surpassing alternative solutions successfully. The CPLEX solver applies various algorithms such as the primal simplex, dual simplex, interior point barrier and mixed-integer methods to effectively tackle a diverse range of optimization problems [6].

The results of the cases are explained below.

4.2.1. Case 1

In Case 1, EDRP and TDRP are not incorporated into the model. The total cost of the EH operation is found as 109787.3993 $. The results for Case 1 are presented in Table 2.

Table 2. Case 1 results

Time	P_t^{grid}	G_t^{grid}	SOC_t^{ESS}	$P_t^{ESS,ch}$	$P_t^{ESS,dch}$
1	148.127	75.032	228.000	120.000	-
2	38.573	82.832	228.000	-	-
3	163.727	93.895	336.000	120.000	-
4	168.478	102.131	444.000	120.000	-
5	142.971	99.713	492.000	53.333	-
6	169.502	112.627	600.000	120.000	-
7	55.338	159.838	600.000	-	-
8	-	191.665	539.896	-	54.094
9	-	210.451	468.118	-	64.600
10	-	199.344	387.897	-	72.199
11	-	240.029	330.729	-	51.451
12	54.928	216.636	330.729	-	-
13	-	227.861	220.102	-	99.565
14	-	234.647	133.986	-	77.504
15	88.040	201.239	120.000	-	12.587
16	83.341	159.184	120.000	-	-
17	62.491	156.133	120.000	-	-
18	67.009	125.228	120.000	-	-
19	59.094	135.627	120.000	-	-
20	56.810	114.625	120.000	-	-
21	50.349	108.082	120.000	-	-
22	37.393	103.740	120.000	-	-
23	19.781	87.925	120.000	-	-
24	37.265	77.856	120.000	-	-

As shown in Table 2, the electricity has not been purchased from the grid during the hours 8-11 and 13-14 that electricity price is high. During these hours, the discharging power of the ESS is utilized to fulfill the electrical demand, while in other hours, electricity is procured from the grid due to favorable, low electricity prices. The ESS is charged in hours 1, 3-6 due to extremely low electricity prices. In these hours, more electricity has been purchased from the grid to charge the ESS and use it when electricity prices are high.

4.2.2. Case 2

In Case 2, the EDRP is incorporated into the EH system in Case 1 and its impact on EH operation has been analyzed. The total cost of the EH operation is found as 106332.5618 $. A decrease in cost has been observed when compared to the Case 1. The results for Case 2 are presented in Table 3.

Table 3. Case 2 results

Time	P_t^{grid}	G_t^{grid}	SOC_t^{ESS}	$P_t^{ESS,ch}$	$P_t^{ESS,dch}$	$P_t^{up,E}$	$P_t^{down,E}$
1	158.760	75.032	228.000	120.000	-	10.420	-
2	52.185	82.832	228.000	-	-	13.340	-
3	178.462	93.895	336.000	120.000	-	14.440	-
4	184.478	102.131	444.000	120.000	-	15.680	-
5	167.502	99.713	492.000	53.333	-	24.040	-
6	186.543	112.627	600.000	120.000	-	16.700	-
7	77.869	159.838	600.000	-	-	22.080	-
8	-	191.665	567.518	-	29.234	-	24.860
9	-	210.451	527.651	-	35.880	-	28.720
10	-	199.344	480.608	-	42.339	-	29.860
11	-	240.029	432.685	-	43.131	-	8.320
12	-	216.636	405.608	-	24.369	-	29.460
13	-	227.861	339.580	-	59.425	-	40.140
14	-	234.647	292.220	-	42.624	-	34.880
15	-	201.239	182.368	-	98.867	-	-
16	111.117	159.184	182.368	-	-	27.220	-
17	-	156.133	138.477	-	39.502	-	21.740
18	-	125.228	138.477	-	-	19.380	-
19	77.278	135.627	138.477	-	-	17.820	-
20	73.647	114.625	138.477	-	-	16.500	-
21	17.686	108.082	120.000	-	16.629	-	15.380
22	51.026	103.740	120.000	-	-	13.360	-
23	29.414	87.925	120.000	-	-	9.440	-
24	50.469	77.856	120.000	-	-	12.940	-

As depicted in Table 3, similar to Case 1, electricity has not been procured from the ESS during hours with high electricity prices. Instead, during hours with lower electricity prices, electricity has been purchased and a portion of it has been stored in the ESS. At the same time, owing to the impact of the EDRP, the load is adjusted downward during the hours when electricity prices are high, effectively curbing costs. Conversely, during hours with lower electricity prices, the load is shifted upward.

4.2.3. Case 3

In Case 3, both the EDRP and the TDRP units are incorporated into the EH system in Case 1 and their impacts on EH operation have been analyzed. The total cost of the EH operation is found as 105675.7576 $. A decrease in cost has been observed when compared to the Case 1 and Case 2. The results for Case 3 are presented in Table 4.

Table 4. Case 3 results

Time	P_t^{grid}	G_t^{grid}	SOC_t^{ESS}	$P_t^{ESS,ch}$	$P_t^{ESS,dch}$	$P_t^{up,E}$	$P_t^{down,E}$	$P_t^{up,H}$	$P_t^{down,H}$
1	163.751	62.803	228.000	120.000	-	10.420	-	-	4.280
2	57.597	69.574	228.000	-	-	13.340	-	-	4.640
3	184.549	78.981	336.000	120.000	-	14.440	-	-	5.220
4	190.705	86.874	444.000	120.000	-	15.680	-	-	5.340
5	173.473	85.084	492.000	53.333	-	24.040	-	-	5.120
6	192.700	97.541	600.000	120.000	-	16.700	-	-	5.280
7	87.081	137.266	600.000	-	-	22.080	-	-	7.900
8	-	218.693	551.909	-	43.282	-	-	9.460	-
9	-	210.451	512.042	-	35.880	-	28.720	-	-
10	-	199.344	464.999	-	42.339	-	29.860	-	-
11	-	279.629	459.697	-	4.771	-	30.840	13.860	-
12	-	216.636	432.620	-	24.369	-	29.460	-	-
13	-	227.861	366.593	-	59.425	-	40.140	-	-
14	-	267.619	295.131	-	64.316	-	-	11.540	-
15	-	233.468	227.683	-	60.703	-	25.273	11.280	-
16	51.415	182.784	227.683	-	-	-	21.847	8.260	-
17	-	177.504	169.136	-	52.693	-	-	7.480	-
18	92.708	110.714	169.136	-	-	19.380	-	-	5.080
19	83.272	120.941	169.136	-	-	17.820	-	-	5.140
20	78.755	102.110	169.136	-	-	16.500	-	-	4.380
21	-	120.882	120.000	-	44.222	-	-	4.480	-
22	56.763	89.683	120.000	-	-	13.360	-	-	4.920
23	34.708	74.953	120.000	-	-	9.440	-	-	4.540
24	55.741	64.942	120.000	-	-	12.940	-	-	4.520

As seen in Table 4, similar to cases 1 and 2, the ESS has not been used for electricity procurement or consumption during periods of high electricity prices. Conversely, when electricity prices are low, some amount of electricity is acquired and stored in the ESS. Moreover, similar to Case 2, the load is adjusted downward during the hours of high electricity prices and it is shifted upward during hours of lower electricity prices, aiming to minimize costs through the influence of the EDRP. In addition, with the effect of the EDRP, the heating demand is elevated during high electricity price hours, leading to an increased procurement of natural gas from the grid. The purpose of this is to ensure that CHP receives more heat and generates more electricity. Thus, when the electricity price is high, the purchase of electricity from the grid is reduced and it causes the cost to decrease. During hours of low electricity prices, the heating demand is adjusted downward, leading to a decrease in the procurement of natural gas from the grid. Consequently, this reduction in heating demand also results in decreased heat generation by the CHP system and an increased reliance on purchasing electricity from the grid.

5. CONCLUSION

In this paper, a MILP model has been developed for the optimal operation of the EH. This model incorporates components such as WES, PVES, CHP, furnace, absorption chiller, ESS, transformer, EDRP and TDRP units. In the simulation studies, the impact of EDRP and TDRP units on cost has been analyzed by considering 3 different cases. The model is implemented in GAMS software and CPLEX is used, which is an efficient and powerful solver for MILP problems. In Case 1, EDRP and TDRP are not added to the model and minimum cost is tried to be obtained. In Case 2, EDRP is added to the model and 3.15% reduction has been observed compared to the Case 1. In Case 3, both EDRP and TDRP are added to the model and the cost is decreased by 3.75% compared to the cost in Case 1. According to the results obtained, it is seen that the proposed problem provides significant cost reduction when the long-term operation planning of the EH is also considered.

To build upon this research, it is recommended to investigate the feasibility of integrating additional RES like geothermal, biomass or hydrogen into the EH system with including Hydrogen Storage System and hydrogen demand. Furthermore, it would be beneficial to analyze the uncertainties related to output from RES, electricity prices and demand. In addition to cost minimization, an objective function could be developed that reduces risks associated with these uncertainties as well as emissions resulting from thermal resources.

Declaration of Ethical Standards

Authors declare to comply with all ethical guidelines including authorship, citation, data reporting, and publishing original research.

Credit Authorship Contribution Statement

Ö. P. AKKAŞ: Methodology, Conceptualization, Resources, Investigation, Writing - review & editing, Supervision.

Y. ARIKAN YILDIZ: Methodology, Conceptualization, Resources, Investigation, Writing -review & editing, Supervision.

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] M. Geidl and G. Andersson, "A modeling and optimization approach for multiple energy carrier power flow," in Proc. IEEE 2005 Power Tech Conference, Russia, 27-30 June 2005.

[2] X. Lu, H. Li, K. Zhou, and S. Yang, "Optimal load dispatch of energy hub considering uncertainties of renewable energy and demand response," *Energy*, vol. 262, pp. 125564, 2023.

[3] A. A. Eladl, M. I. El-Afifi, M. A. Saeed, and M. M. El-Saadawi, "Optimal operation of energy hubs integrated with renewable energy sources and storage devices considering CO_2 emissions," *Electrical Power and Energy Systems*, vol. 117, p. 105719, 2020.

[4] D. Rakipour and H. Barat, "Probabilistic optimization in operation of energy hub with participation of renewable energy resources and demand response," *Energy*, vol. 173, pp. 384-399, 2019.

[5] M. Tian, A. G. Ebadi, K. Jermsittiparsert, M. Kadyrov, A. Ponomarev, N. Javanshir, and S. Nojavan, "Risk-based stochastic scheduling of energy hub system in the presence of heating network and thermal energy management," *Applied Thermal Engineering*, vol. 159, p. 113825, 2019.

[6] M. Nasir, A. R. Jordehi, M. Tostado-Veliz, V. S. Tabar, S. A. Mansouri, and F. Jurado, "Operation of energy hubs with storage systems, solar, wind and biomass units connected to demand

response aggregators," *Sustainable Cities and Society*, vol. 83, p. 103974, 2022.

[7] V. Davatgaran, M. Saniei, and S. S. Mortazavi, "Optimal bidding strategy for an energy hub in energy market," *Energy*, vol. 148, pp. 482-493, 2018.

[8] M. J. Vahid-Pakdel, S. M. Nojavan, B. Mohammadi-ivatloo, and K. Zare, "Stochastic optimization of energy hub operation with consideration of thermal energy market and demand response," *Energy Conversion and Management*, vol. 145, pp. 117–128, 2017.

[9] E. Shahrabi, S. M. Hakimi, A. Hasankhani, G. Derakhshan, and B. Abdi, "Developing optimal energy management of energy hub in the presence of stochastic renewable energy resources," *Sustainable Energy, Grids and Networks*, vol. 26, p. 100428, 2021.

[10] Y. Cao, Q. Wang, J. Du, S. Nojavan, K. Jermsittiparsert, and N. Ghadimi, "Optimal operation of CCHP and renewable generation-based energy hub considering environmental perspective: An epsilon constraint and fuzzy methods," *Sustainable Energy, Grids and Networks*, vol. 20, p. 100274, 2019.

[11] F. Jamalzadeh, A. H. Mirzahosseini, F. Faghihi, and M. Panahi, "Optimal operation of energy hub system using hybrid stochastic-interval optimization approach," *Sustainable Cities and Society*, vol. 54, p. 101998, 2020.

[12] A. Dolatabadi and B. Mohammadi-Ivatloo, "Stochastic risk-constrained scheduling of smart energy hub in the presence of wind power and demand response," *Applied Thermal Engineering*, vol. 123, pp. 40–49, 2017.

[13] S. Pazouki, M. Haghifam, and A. Moser, "Uncertainty modeling in optimal operation of energy hub in presence of wind, storage and demand response," *Electrical Power and Energy Systems*, vol. 61, pp. 335–345, 2014.

[14] S. Pazouki and M. Haghifam, "Optimal planning and scheduling of energy hub in presence of wind, storage and demand response under uncertainty," *Electrical Power and Energy Systems*, vol. 80, pp. 219–239, 2016.

[15] V. V. Thang, T. Ha, Q. Li, and Y. Zhang, "Stochastic optimization in multi-energy hub system operation considering solar energy resource and demand response," *Electrical Power and Energy Systems*, vol. 141, p. 108132, 2022.

[16] M. Majidi, S. Nojavan, and K. Zare, "A cost-emission framework for hub energy system under demand response program," *Energy*, vol. 134, pp. 157-166, 2017.

[17] M. H. Shams, M. Kia, M. Heidari, A. Lotfi, M. Shafie-khah, and J. P. S. Catalao, "Optimal operation of electrical and thermal resources in microgrids with energy hubs considering uncertainties," *Energy*, vol. 187, p. 115949, 2019.

[18] S. A. Mansouri, A. Ahmarinejad, M. Ansarian, M. S. Javadi, and J. P. S. Catalao, "Stochastic planning and operation of energy hubs considering demand response programs using Benders decomposition approach," *Electrical Power and Energy Systems*, vol. 120, p. 106030, 2020.

[19] W. Jiang, X. Wang, H. Huang, D. Zhang, and N. Ghadimi, "Optimal economic scheduling of microgrids considering renewable energy sources based on energy hub model using demand response and improved water wave optimization algorithm," *Journal of Energy Storage*, vol. 55, p. 105311, 2022.

[20] A. Soroudi, M. Aien, and M. Ehsan, "A probabilistic modeling of photovoltaic modules and wind power generation impact on distribution networks," *IEEE Systems Journal*, vol. 6, no. 2, pp. 254–259, 2012.

[21] B. Ozerdem, S. Ozer, and M. Tosun, "Feasibility study of wind farms: A case study for Izmir, Turkey," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 94, no. 10, pp. 725-743, 2006.

[22] S. Hadayeghparast, A. S. Farsangi, and H. Shayanfar, "Day-ahead stochastic multi-objective economic/emission operational scheduling of a large scale virtual power plant," *Energy*, vol. 172, pp. 630-646, 2019.

[23] A. Soroudi, *Power System Optimization Modeling in GAMS*. Springer, 2017.

[24] GAMS. [Online]. Available: http://www.GAMS.com. [Accessed Feb. 26, 2024].