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A General Model for Energy Hub Economic Dispatch

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Abstract-This paper proposes a new optimization algorithm, namely Self-Adoptive Learning with Time 6 7 Varying Acceleration Coefficient-Gravitational Search Algorithm (SAL-TVAC-GSA), to solve highly 8 nonlinear, non-convex, non-smooth, non-differential, and high-dimension single- and multi-objective 9 Energy Hub Economic Dispatch (EHED) problems. The presented algorithm is based on GSA 10 considering three fundamental modifications to improve the quality solution and performance of original 11 GSA. Moreover, a new optimization framework for economic dispatch is adapted to a system of energy 12 hubs considering different hub structures, various energy carriers (electricity, gas, heat, cool, and compressed air), valve-point loading effect and prohibited zones of electric-only units, as well as the 13 different equality and inequality constraints. To show the effectiveness of the suggested method, a high-14 15 complex energy hub system consisting of 39 hubs with 29 structures and 76 energy (electricity, gas, and 16 heat) production units is proposed. Two individual objectives including energy cost and hub losses are 17 minimized separately as two single-objective EHED problems. These objectives are simultaneously minimized in the multi-objective optimization. Results obtained by SAL-TVAC-GSA in terms of quality 18 19 solution and computational performance are compared with Enhanced GSA (EGSA), GSA, Particle 20 Swarm Optimization (PSO), and Genetic Algorithm (GA) to demonstrate the ability of the proposed 21 algorithm in finding an operating point with lower objective function.

Keywords-Economic dispatch, energy hub, energy hub economic dispatch, gravitational search
 algorithm, self-adoptive learning with time varying acceleration coefficient-gravitational search
 algorithm, optimization.

25 **1. Introduction**

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26 Future vision of energy networks including several energy carriers in the form of multi-carrier systems 27 [1] (also, called multiple energy carrier networks [2] or hybrid systems [3]), allows more flexibility in the 28 integrated network operation and optimization [4,5]. In fact, various infrastructures can affect each other 29 in terms of energy flow, storage, etc. In the meantime, energy hubs play an essential role in the 30 connection points between different infrastructures allowing energy flow through various networks. Combination of several converters in hubs provides necessary motivations to integrate multiple energy 31 32 carriers [3]. Some converters such as CHP devices [6–9] and tri-generations [10–13] in the hubs are two 33 attractive cases which can establish more effective energy conversion between different carriers [1,3,4,6].

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34 In this regards, other elements (such as heater exchangers) may operate with a single carrier. In this view

point, various carriers can be consumed by different hub structures to provide different forms of energy at

the output port.

37 Proposing the different optimization problems for electrical systems will be lead to introduce two problems, namely Multi-Carrier System Optimal Power Flow (MCSOPF) and Energy Hub Optimal 38 Dispatch (EHOD), for hybrid systems. The first one, optimizes the energy flow through various networks 39 40 based on a desirability e.g. energy cost, emission cost, energy loss, and etc. [1,2,4]. So, the system 41 condition in terms of all control and state variables, energy flows and the other quantities can be determined. Due to different structures associated with various energy infrastructures, the MCSOPF is a 42 non-convex, non-smooth, nonlinear, and high-dimension optimization problem. Therefore, finding the 43 global optimum could not to be guaranteed [3]. The EHOD optimizes a single hub neglecting the energy 44 45 transmission losses [2]. The basic questions which should be answered by EHOD are how much of the available carriers at the input port of a hub should be consumed and how should they be converted in 46 47 order to satisfy the demands at the hub outputs. In other words, this optimization process determines the optimal energy input subject to energy flow through the hub and load supplying. 48

49 The work presented in [2], introduces the hub concept and its modeling and optimizes a hybrid system including electrical and gas networks. The MCSOPF problem in [2] provides a general formulation which 50 51 can be employed for various electrical and pipeline systems. In this context, [1] applied a decomposition method to MCSOPF. This approach uses virtual units and dummy variables to construct the problem. 52 53 This makes a complex OPF problem involved with additional variables and constraints. An energy flow 54 optimization of hybrid systems based on a modified version of teaching-learning algorithm has been reported in [4]. This reference optimizes multicarrier system including electrical, gas, and heat 55 56 infrastructures. Authors of [3], analyzed the impact of heating systems on hybrid networks in terms of OPF. Another method based on employing an appropriate set of dependent variables has been proposed in 57 58 [14]. In fact, in order to convert irregular equations into a regular set, it eliminates the addition of any new 59 variable. A similar approach has been reported in [15]. In [16], a Gravitational Search Algorithm with 60 Time Varying Acceleration Coefficient (TVAC-GSA) has been applied to MCSOPF problem. This method is based on the gravitational law and law of motion. In [17], multi-agent systems are used to 61 62 optimize and control multiple energy carriers. The work reported in [18], studies the interactions in district electricity and heating systems. A combined analysis of these grids can be found in [19]. Optimal 63 operation of integrated electrical and heating systems to accommodate the intermittent renewable sources 64 has been proposed in [20]. Ref. [21] presented a model for integrated analysis of electricity, heat and gas 65 networks. A similar work to form an integrated OPF for multiple energy networks has been developed in 66 67 [22].

68 Ref. [2] suggested EHOD problem of an energy hub and described the related optimization process. 69 Effect of energy hubs on the hybrid systems has been discussed in [23]. A generic framework for modeling of energy systems based on the hub concept has been suggested in [24]. In [25], a medium-term 70 energy hub management based on electricity price as well as wind uncertainty has been documented. Ref. 71 [26] modeled an Economic Dispatch (ED) of multiple energy carriers considering wind energy (i.e. [27]) 72 through a multi-agent genetic algorithm. This reference considered only one structure for all hubs with 73 three forms of energy and without investigating a set of hubs which supply load. Also, in [26], the energy 74 cost has been minimized only without considering the optimization of hub losses or a multi-objective 75 76 problem (such as simultaneously minimizing the energy cost and losses of a set of hubs). In addition, 77 some operational challenges such as valve-point loading effect and prohibited zones have not been taken 78 into account.

79 1.1. Motivation, contribution, and novelty

80 ED in the power systems is a well-known problem and it is one of the most heavily used tools in the 81 power system studies. It responses to schedule the committed outputs of all available generation units to meet the load demand at the minimum operating cost as well as satisfying different equality and 82 inequality constraints [28]. The CHPED [29] is an extension version of the economic dispatch and can be 83 84 considered as a special case of MCS problems in which two forms of energy, i.e. electricity and heat, are optimized simultaneously [6]. In the viewpoint of hub, the CHPED can be modeled with different hubs 85 constructed by three elements including transformer (with 100% efficiency), CHP unit, and heater 86 exchanger (with 100% efficiency). Fig. 1 shows this concept. 87





Fig. 1. A general representation of CHPED based on the hub concept

In this paper, motivation of CHPED modeling, based on the mentioned viewpoint, is extended to various hub structures with different converters and elements. So, an optimization framework is presented to formulate this new problem. It is mainly due to the fact that at this stage of the advancement of MCS, there is still needs to be put under examination in both modeling and operating concerns. Economic energy dispatch and conversion in the hubs are two main issues in the MCSs. In this condition, the classical ED methods should be modified to meet the system requirements like optimal conversion between different carriers.

98 The new proposed modeling, which is called Energy Hub Economic Dispatch (EHED), states a general 99 economic representation covering a wide range of energies and hubs including different converters. This 100 problem schedules the committed input carriers available at the hub inputs to meet different types of 101 demands at minimum operating cost while satisfying various operational constraints. In other words, 102 EHED allows finding an optimal operating point in terms of satisfying different equality and inequality constraints, supplying the various forms of load demands efficiently and economically, and searching the 103 global optimum (or a less expensive solution) based on the objective function. Accordingly, three 104 objective functions including energy cost of input carriers (as a single-objective), energy hub losses (as 105 106 another single-objective), and a combination of them (as multi-objective) with different operational constraints are formulated to construct EHED problem. Therefore, the EHED problem is a nonlinear, non-107 108 convex, and high dimension one. It should be noted that to the best of authors' knowledge, none of the past researchers and publications have considered the mentioned extension with new futures to form the 109 explained EHED problem. 110

111 In order to efficiently optimize the proposed optimization problem, a new modified version of Gravitational Search Algorithm (GSA), namely Self-Adaptive Learning with Time Varying Acceleration 112 113 Coefficient GSA (SAL-TVAC-GSA), is suggested. The proposed algorithm is based on the Newtonian 114 laws of gravitation and motion. In the suggested algorithm, three new strategies are considered to improve 115 the performance of the original GSA and avoid trapping in local optima: 1) self-adaptive learning strategy; 2) considering time varying acceleration coefficient (a new strategy for gbest-guided); 3) a novel 116 117 gravitational constant. The main feature of the proposed approach is due to its ability in solving quite large EHED problems yielding economical benefits with regard to the other tested algorithms. In fact, the 118 119 suggested algorithm can search a better solution with a good convergence characteristic and a computational time fully compatible with operational planning time requirements. It should be noted that 120 the contribution in this area derives from the capability of the suggested algorithm in being robust, i.e. 121 always capable of finding a good quality solution without convergence problems and mostly yielding a 122 better optimum which results in economical benefits which is our main performance indicator. Moreover, 123 124 as long as authors know the proposed algorithm is a new optimization technique and has not been tested on this kind of problems before. 125

- 126 In summary, the main novelties and contribution of this work are:
- Proposing a general, simple, and suitable model for EHED in order to optimize various forms of energies as well as hub's conversions and flows. Furthermore, the energy hub-losses (instead of power losses only) are considered in the formulations. The presented formulation allows considering different carriers and taking into account the interactions between them.
- Covering different hubs with various structures. Different hub elements can be considered in the proposed model and each hub can be represented by a coupling matrix to demonstrate the interactions between various inputs and outputs. This subject is formulated as an equality constraint in EHED problem.
- Optimizing both single- and multi-objective EHED problems in terms of energy cost and hub losses. The hub losses are carried out as one of objectives in addition to the cost of various carriers.
- Considering the real-world conditions like valve-point loading effect and prohibited zones of electric-only units in formulations.
- 140 Suggestion a new and powerful optimization algorithm, namely SAL-TVAC-GSA, to optimize the suggested EHED problem. The proposed optimization algorithm employs three fundamental 141 modifications to enhance the quality solution and performance of the original GSA. The main 142 characteristics and details of this new method can be found in section 4. Moreover, the obtained 143 results demonstrate the ability and performance of the proposed optimization algorithm in 144 145 finding a better quality solution than the other reported algorithms. Some advantages of the new algorithm are its simplicity of implementation, its accuracy, and its fast convergence to the 146 optimal solution while satisfying all constraints. 147

Demonstrating a new and complex test case to analyze the superior performance of the proposed optimization algorithm in terms of both solution accuracy and convergence performances.

150 *1.2. Organization*

151 The rest of this work is organized as follows: in section 2, the energy hub concept and the related 152 general model as well as structures of the considered hubs are illustrated. In section 3, formulation of the proposed EHED problem in terms of different objective functions (both single- and multi-objective 153 154 problems) and associated constraints is presented. Main structure of original GSA is described in section 155 4. Moreover, the suggested modifications applied to GSA to construct the proposed SAL-TVAC-GSA are presented in this section. Different steps of the suggested algorithm to solve EHED problem is described 156 157 in section 5. The effectiveness of the proposed approach is verified by comparisons with various optimization algorithms such as TVAC-GSA, Enhanced GSA (EGSA), GSA, Particle Swarm 158 159 Optimization (PSO), and Genetic Algorithm (GA) in Section 6. Finally, we will draw the conclusions.

160 **2. Energy hub**

161 *2.1. Main structure*

Generally, each energy hub makes an interface between delivered energy (by transmission networks 162 and/or energy sources) and loads. In other words, various forms of energy (such as electricity, natural gas, 163 etc.) are consumed at the input ports of a hub unit and different energy services (such as electricity, heat, 164 165 coal, etc.) are provided at its output ports. This unit allows to integrate an arbitrary number of energy 166 carriers and products [2]. Fig. 2 illustrates this concept. In this figure, the bidirectional arrow of 167 conversion describes the energy flowing from input side to demand side and vice versa, e.g. electrical power flow through a transformer. However, for instance, in a gas turbine, energy only flows from input 168 169 port to the output one.



170 171

Fig. 2. A general and simple structure of an energy hub

- 172 The basic energy hub elements can be categorized as follows:
- Direct connection: this type delivers an input carrier to the output without converting it into another form or without significantly changing its quality (e.g., voltage and pressure). Electric cables, overhead lines, and pipelines are some examples in this regard.
- Converter: it transforms energy into a different form or quality such as steam and gas turbines, combustion engines, electric machines, and fuel cells.
- Storage devices: they store different forms of energy e.g. thermal storage capacity and electrical storage device.

Generally, the power plants (e.g. co- and tri-generations), industrial plants (e.g. refineries), big buildings (e.g. airports, hospitals, and shopping malls), and bounded geographical areas (e.g. cities) can be modeled as energy hubs. In this view point, an energy hub can be applied to any size of the modeled system [2,30] (e.g. at neighborhood scale [31]). Converter elements or combinations of different converters in the form of energy hubs may have
 multiple in- and out-puts. Four types of conversions can be classified according to the number of in- and
 out-puts [2] as follows:

- Single Input and Single Output (SISO): the gas furnace is an example which converts natural gas to heat.
- Single Input and Multiple Output (SIMO): e.g. trigeneration which consumes natural gas and provides cool, heat, and electricity at output port.
- Multiple Input and Single Output (MISO): heat pump is an appropriate example which converts heat and electricity to heat.
- Multiple Input and Multiple Output (MIMO): an example of this type is reversible fuel cell which provides heat and electricity by consuming water and hydrogen [2].

A general MIMO model covering couplings can be formulated as follows [2]. According to (1), the mapping of input carriers to output ones of an energy hub can be modeled through a coupling matrix **C**.

$$\begin{bmatrix} E_{\alpha}^{\text{out}} \\ E_{\beta}^{\text{out}} \\ \vdots \\ E_{\omega}^{\text{out}} \end{bmatrix} = \underbrace{\begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \dots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \dots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \dots & c_{\omega\omega} \end{bmatrix}}_{\mathbf{C}} \begin{bmatrix} E_{\alpha}^{\text{in}} \\ E_{\beta}^{\text{in}} \\ \vdots \\ E_{\omega}^{\text{in}} \end{bmatrix}$$
(1)

197 In (1), **Input** denotes the vector of energy inputs; **Output** is the energy outputs vector; **C** illustrates the 198 coupling matrix; moreover, subscript { α , β , ...} describes the energy carriers such as electricity, natural 199 gas, etc.; and the entries of matrix **C** (i.e. $c_{\alpha\alpha}$, $c_{\alpha\beta}$, and etc.) are coupling factors.

200 Energy conversion in (1) is handled by coupling factors through relating an input to a certain output. Note that, as indicated in [2], in the simple cases such as transformers and gas furnaces, the coupling 201 202 factor represents the steady state energy efficiency. Also, according to [2], in this paper, it is assumed that the coupling factors show constant efficiencies and so, the devices operate with constant efficiencies. In 203 contrast, for a MIMO energy hub, the coupling factors are in general no longer equal to converter 204 efficiencies. Since the received energy at input port may be split up to several converters, other coupling 205 206 factors, namely *dispatch factors*, have to be considered. These factors define how energy flows from an 207 input carrier are distributed among the hub elements. For a specific hub structure (see the following subsection) a similar conclusion can be considered for the output port. Therefore, in this paper, factors v208 209 (or v_1) is employed for input ports and also factor v_2 is used for output port, if required. Therefore, each 210 coupling factor contains "dispatch factor×converter efficiency" [2] (this concept will be employed in the next subsection). In this view point, the matrix C establishes a linear transformation because of the 211 212 assumed constant efficiencies.

213 2.2. Different types of considered energy hubs

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214 Main assumptions in this subsection are as follows:

- Within each energy hub, losses only occur in the convertor devices.
- Storage devices according to [2,32] can be included. But, it will not be considered explicitly here.
- Gross heating value is taken to be unit (for more details see [2]).

In this paper, 29 hub structures are investigated as illustrated in Fig. 3. In this figure, there are sixelements as follows:

- Transformer: it delivers and provides electrical energy at its input and output, respectively.
- CHP: this device consumes the natural gas to produce electricity and heat.

- Combined Heat, Cool, and Power (CHCP): it converts the natural gas to electricity, heating, and cooling.
- Gas Furnace (GF): this device burns the natural gas and delivers heat.
- Heater Exchanger (HE): it consumes and provides heating at its input and output, respectively.
- Compressor air: this device products compressed air from electricity.

Based on these elements, five carriers including electricity, heat, cool, compressed air, as well as natural gas are denoted by subscripts e, h, c, a, and g, respectively. Energy conversion of the hubs presented in Fig. 3 can be stated as follows:

Hub #1: this hub consists of only one transformer unit. The coupling matrix as well as the related input and output energy vectors can be represented as:

$$E_e^{\text{out}} = \begin{bmatrix} \widetilde{\eta}_{\text{T}} \\ \widetilde{\eta}_{\text{T}} \end{bmatrix} E_e^{\text{in}}$$
(2)

- 232 where $\eta_{\rm T}$ denotes the transformer efficiency.
- Hub #2: it contains only one CHP unit and is modeled as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overline{\eta_{\text{CHP}_e}} \\ c_{gh} \\ \overline{\eta_{\text{CHP}_h}} \end{bmatrix} E_g^{\text{in}}$$
(3)

- where η_{CHP_e} and η_{CHP_h} are the electrical and heat efficiencies, respectively.
- Hub #3: a CHCP unit constructs this hub which can be represented as:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_c^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overline{\eta_{\text{CHCP}_e}} \\ c_{gh} \\ \overline{\eta_{\text{CHCP}_h}} \\ c_{gc} \\ \overline{\eta_{\text{CHCP}_c}} \end{bmatrix} E_g^{\text{in}}$$
(4)

- where η_{CHCP_e} , η_{CHCP_h} , and η_{CHCP_c} show the electrical, heat, and cool efficiencies of CHCP unit, respectively.
- Hub #4: this hub includes only one furnace and is formulated as:

$$E_h^{\text{out}} = \left[\frac{\hat{\eta}_{\text{GF}}}{\hat{\eta}_{\text{GF}}}\right] E_g^{\text{in}} \tag{5}$$

- 239 where the furnace's efficiency is denoted by η_{GF} .
- Hub #5: one heater exchanger is the main structure of this hub and can be stated as follows:

$$E_h^{\text{out}} = \left[\widetilde{\eta_{\text{HE}}} \right] E_h^{\text{in}} \tag{6}$$

- 241 where η_{HE} is the HE's efficiency.
- Hub #6: the electricity and gas are consumed by transformer and CHP unit located in this hub to provide electricity and heating at the output through the following mathematical configuration:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_e^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ee} & c_{ge} \\ \widetilde{\eta}_{\mathrm{T}} & \widetilde{\eta}_{\mathrm{CHP}_e} \\ c_{eh} & c_{gh} \\ \widetilde{0} & \widetilde{\eta}_{\mathrm{CHP}_h} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(7)

• Hub #7: this hub produces electricity, heating as well as compressed air by employing the electrical energy, as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{(1-\nu)\eta_{\text{T}}}^{c_{ee}} \\ \overbrace{\nu\eta_{C_h}\eta_{\text{T}}}^{c_{eh}} \\ \overbrace{\nu\eta_{C_a}\eta_{\text{T}}}^{c_{ea}} \end{bmatrix} E_e^{\text{in}}$$
(8)

- 246 where η_{C_h} and η_{C_a} are compressor air's efficiencies related to the heat and air, respectively.
- Hub #8: electricity, heating, and cooling can be provided by this hub through consuming the electrical and gas energies as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_c^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ee}^{ee} & c_{ge} \\ \overline{\eta}_{\text{T}}^{\text{c}} & \overline{\eta}_{\text{CHCP}_e} \\ \overline{0} & \overline{\eta}_{\text{CHCP}_h} \\ c_{ec} & c_{gc} \\ \overline{0} & \overline{\eta}_{\text{CHCP}_c} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(9)

Hub #9: one CHP unit and one gas furnace convert the dispatched natural gas into the electricity
 and heating through the following formula:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ge} \\ \hline \nu \eta_{\text{CHP}_e} \\ c_{gh} \\ \hline \nu \eta_{\text{CHP}_h} + (1 - \nu) \eta_{\text{GF}} \end{bmatrix} E_g^{\text{in}}$$
(10)

• Hub #10: two forms of energy including heating and gas at the hub input, are converted to electrical energy and heating for customers as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \end{bmatrix} = \begin{bmatrix} \widetilde{\eta_{\text{CHP}_e}} & \widetilde{0} \\ \widetilde{\eta_{\text{CHP}_h}} & \widetilde{0}_{\text{hE}} \\ \widetilde{\eta_{\text{CHP}_h}} & \widetilde{\eta_{\text{HE}}} \end{bmatrix} \begin{bmatrix} E_g^{\text{in}} \\ E_h^{\text{in}} \end{bmatrix}$$
(11)

• Hub #11: this hub is constructed by employing and CHCP units and described as:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_e^{\text{out}} \\ E_c^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overline{\eta_{\text{CHCP}_e}} & \overline{0} \\ \overline{\eta_{\text{CHCP}_h}} & \overline{\eta_{\text{HE}}} \\ \overline{\eta_{\text{CHCP}_h}} & \overline{\eta_{\text{HE}}} \\ \overline{\eta_{\text{CHCP}_c}} & \overline{0} \end{bmatrix} \begin{bmatrix} E_g^{\text{in}} \\ E_h^{\text{in}} \end{bmatrix}$$
(12)

• Hub #12: it provides heating, cooling, and electricity by using the natural gas based on the following representation:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_c^{\text{out}} \end{bmatrix} = \begin{bmatrix} \frac{c_{ge}}{\nu \eta_{\text{CHCP}_e}} \\ \frac{c_{gh}}{\nu \eta_{\text{CHCP}_h} + (1 - \nu) \eta_{\text{GF}}} \\ \frac{c_{gc}}{\nu \eta_{\text{CHCP}_c}} \end{bmatrix} E_g^{\text{in}}$$
(13)

• Hub #13: this hub delivers two input carriers (i.e. electricity and heating) to the output without converting them into another form of energy as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ee} & c_{he} \\ \widetilde{\eta}_{T} & \widetilde{0} \\ c_{eh} & c_{hh} \\ \widetilde{0} & \widetilde{\eta}_{\text{HE}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_h^{\text{in}} \end{bmatrix}$$
(14)

• Hub #14: transformer and GF provide electrical and heating energies for loads as:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ee} & c_{ge} \\ \widetilde{\eta}_{T} & \widetilde{0} \\ c_{eh} & c_{gh} \\ \widetilde{0} & \widetilde{\eta}_{GF} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(15)

Hub #15: in this hub, two forms of energies, i.e. heating and gas, are converted to heating as below:

$$E_{h}^{\text{out}} = \begin{bmatrix} c_{gh} & c_{hh} \\ \widehat{\eta}_{\text{GF}} & \widehat{\eta}_{\text{HE}} \end{bmatrix} \begin{bmatrix} E_{g}^{\text{in}} \\ E_{h}^{\text{in}} \end{bmatrix}$$
(16)

Hub #16: delivering four forms of energy including electricity, heating, cooling, and compressed air by employing only the natural gas is performed through this hub through as following:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_e^{\text{out}} \\ E_c^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{(1-\nu)\eta_{\text{CHCP}_e}}^{c_{ge}} \\ \overbrace{\eta_{\text{CHCP}_h} + \nu\eta_{\text{CHCP}_e}\eta_{C_h}}^{c_{gh}} \\ \overbrace{\eta_{\text{CHCP}_c}}^{c_{gc}} \\ \overbrace{\eta_{\text{CHCP}_c}}^{c_{ga}} \\ \overbrace{\nu\eta_{\text{CHCP}_e}\eta_{C_a}}^{c_{ga}} \end{bmatrix} E_g^{\text{in}}$$
(17)

Hub #17: it is similar to previous structure; but, CHCP unit has been replaced by a CHP.
 Mathematical representation of this hub, which provides three carriers (i.e. electricity, heating, and compressed air) from the natural gas, is as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \frac{c_{ge}}{(1-\nu)\eta_{\text{CHP}_e}} \\ \frac{c_{gh}}{\eta_{\text{CHP}_h} + \nu\eta_{\text{CHP}_e}\eta_{\text{C}_h}} \\ \frac{c_{ga}}{\nu\eta_{\text{CHP}_e}\eta_{\text{C}_a}} \end{bmatrix} E_g^{\text{in}}$$
(18)

• Hub #18: this hub consists of three elements (i.e. transformer, CHCP, and HE) to convert electricity, gas, and heat into electricity, heating, and cooling as below:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_e^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ee} & c_{ge} & c_{he} \\ \widetilde{\eta_T} & \widetilde{\eta_{\text{CHCP}_e}} & \widetilde{0} \\ c_{eh} & c_{gh} & c_{hh} \\ \widetilde{0} & \widetilde{\eta_{\text{CHCP}_h}} & \widetilde{\eta_{\text{HE}}} \\ c_{ea} & c_{ga} & c_{ha} \\ \widetilde{0} & \widetilde{\eta_{\text{CHCP}_c}} & \widetilde{0} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \\ E_h^{\text{in}} \end{bmatrix}$$
(19)

Hub #19: heater exchanger, CHP, and transformer construct this hub to deliver heating and electrical energy through consuming and converting electricity, gas, and heating as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_e^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ee} & c_{ge} & c_{he} \\ \widehat{\eta}_{\mathrm{T}} & \widehat{\eta}_{\mathrm{CHP}_e} & \widehat{0} \\ c_{eh} & c_{gh} & c_{hh} \\ \widehat{0} & \widehat{\eta}_{\mathrm{CHP}_h} & \widehat{\eta}_{\mathrm{HE}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \\ E_h^{\text{in}} \end{bmatrix}$$
(20)

• Hub #20: in this hub, three elements including transformer, CHP, and gas furnace, convert electricity and gas into electricity and heating as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_e^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ee} & c_{ge} \\ \overline{\eta_T} & \overline{\nu\eta_{\text{CHP}_e}} \\ c_{eh} & c_{gh} \\ \overline{0} & \overline{\nu\eta_{\text{CHP}_h} + (1-\nu)\eta_{\text{GF}}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(21)

Hub #21: it employs CHCP, furnace, and transformer through the following mathematical configuration.

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_c^{\text{out}} \end{bmatrix} = \begin{bmatrix} c_{ee} & c_{ge} \\ \overline{\eta}_T & \overline{\nu\eta_{\text{CHCP}_e}} \\ c_{eh} & c_{gh} \\ \overline{0} & \overline{\nu\eta_{\text{CHCP}_h} + (1 - \nu)\eta_{\text{GF}}} \\ c_{ec} & c_{gc} \\ \overline{0} & \overline{\nu\eta_{\text{CHCP}_c}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(22)

Hub #22: transformer, CHCP, and compressor air convert electricity and heating into electricity, heating, cooling, and compressed air through the following conversion.

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_a^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{(1-\nu)\eta_{\text{T}}}^{c_{ee}} & \overbrace{(1-\nu)\eta_{\text{CHCP}_e}}^{c_{ge}} \\ \overbrace{\nu\eta_{\text{T}}\eta_{\text{C}_h}}^{c_{eh}} & \overbrace{\eta_{\text{CHCP}_h} + \nu\eta_{\text{CHCP}_e}\eta_{\text{C}_h}}^{c_{gh}} \\ \overbrace{0}^{c_{ec}} & c_{gc}}^{c_{gc}} \\ \overbrace{0}^{c_{ea}} & \overbrace{\eta_{\text{CHCP}_c}}^{c_{ga}} \\ \overbrace{\nu\eta_{\text{T}}\eta_{\text{C}_a}}^{c_{ga}} & \overbrace{\nu\eta_{\text{CHCP}_e}\eta_{\text{C}_a}}^{c_{ga}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(23)

• Hub #23: this hub equipped with transformer, CHP, and compressor air as:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{(1-\nu)\eta_{\text{T}}}^{c_{ee}} & \overbrace{(1-\nu)\eta_{\text{CHP}_e}}^{c_{ge}} \\ \overbrace{\nu\eta_{\text{T}}\eta_{\text{C}_h}}^{c_{eh}} & \overbrace{\eta_{\text{CHP}_h} + \nu\eta_{\text{CHP}_e}\eta_{\text{C}_h}}^{c_{gh}} \\ \overbrace{\nu\eta_{\text{T}}\eta_{\text{C}_a}}^{c_{ea}} & \overbrace{\nu\eta_{\text{CHP}_e}\eta_{\text{C}_a}}^{c_{ga}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(24)

Hub #24: four elements including transformer, CHCP, gas furnace, and compressor air deliver four types of carriers (i.e. electricity, heating, cooling, and compressed air) by using two forms of energy consisting of electrical and gas as below:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \\ E_e^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{\nu_{ee}}^{c_{ee}} & \overbrace{\nu_1(1-\nu_2)\eta_{\text{CHCP}_e}}^{c_{ge}} \\ \overbrace{\nu_2\eta_T\eta_{C_h}}^{c_{eh}} & \overbrace{\nu_1\eta_{\text{CHCP}_h} + (1-\nu_1)\eta_{\text{GF}} + \nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{C_h}}^{c_{gh}} \\ \overbrace{\nu_2\eta_T\eta_{C_h}}^{c_{ec}} & \overbrace{\nu_1\eta_{\text{CHCP}_c}}^{c_{gc}} \\ \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}}^{c_{ga}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{C_a}}^{c_{ga}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(25)

• Hub #25: the structure of this hub is as previous hub; but, CHCP unit has been replaced by a CHP one. So, the energy conversion can be formulated as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_e^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \frac{c_{ee}}{(1-\nu_2)\eta_{\text{T}}} & \frac{c_{ge}}{\nu_1(1-\nu_2)\eta_{\text{CHP}_e}} \\ \frac{c_{eh}}{\nu_2\eta_{\text{T}}\eta_{\text{C}_h}} & \frac{c_{gh}}{\nu_1\eta_{\text{CHP}_h} + (1-\nu_1)\eta_{\text{GF}} + \nu_1\nu_2\eta_{\text{CHP}_e}\eta_{\text{C}_h}} \\ \frac{c_{ea}}{\nu_2\eta_{\text{T}}\eta_{\text{C}_a}} & \frac{c_{ga}}{\nu_1\nu_2\eta_{\text{CHP}_e}\eta_{\text{C}_a}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \end{bmatrix}$$
(26)

compressed air through transformer, CHCP, HE, and compressor air as below:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_h^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{(1-\nu)\eta_{\text{T}}}^{c_{ee}} & \overbrace{(1-\nu)\eta_{\text{CHCP}_e}}^{c_{ge}} & \overbrace{0}^{c_{he}} \\ \overbrace{\nu\eta_{\text{T}}\eta_{\text{C}_h}}^{c_{gh}} & \overbrace{\eta_{\text{CHCP}_h} + \nu\eta_{\text{CHCP}_e}\eta_{\text{C}_h}}^{c_{gh}} & \overbrace{\eta_{\text{HE}}}^{c_{hh}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ F_e^{\text{in}} \end{bmatrix}$$
(27)

Hub #26: it transforms electricity, gas, and heating into electricity, heating, cooling, and

$$\begin{bmatrix} E_h \\ E_c^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \nu \eta_{\text{T}} \eta_{C_h} & \eta_{\text{CHCP}_h} + \nu \eta_{\text{CHCP}_e} \eta_{C_h} & \eta_{\text{HE}} \\ c_{ec} & c_{gc} & c_{hc} \\ \hline 0 & \eta_{\text{CHCP}_c} & \hline 0 \\ c_{ea} & c_{ga} & c_{ha} \\ \hline \nu \eta_{\text{T}} \eta_{C_a} & \overline{\nu \eta_{\text{CHCP}_e} \eta_{C_a}} & \hline 0 \end{bmatrix} \begin{bmatrix} E_g^{\text{in}} \\ E_h^{\text{in}} \end{bmatrix}$$
(27)

 • Hub #27: electricity, gas, and heating are converted into electricity, heating, and compressed air by this hub equipped with transformer, HE, CHP, and compressor air. The mathematical representation of this energy conversion can be stated as:

$$\begin{bmatrix} E_e^{\text{out}}\\ E_e^{\text{out}}\\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{(1-\nu)\eta_{\mathrm{T}}}^{c_{ee}} & \overbrace{(1-\nu)\eta_{\mathrm{CHP}_e}}^{c_{ge}} & \overbrace{0}^{c_{he}}\\ \overbrace{(\eta_{\mathrm{T}}\eta_{\mathrm{C}_h}}^{c_{eh}} & \overbrace{\eta_{\mathrm{CHP}_h}+\nu\eta_{\mathrm{CHP}_e}\eta_{\mathrm{C}_h}}^{c_{gh}} & \overbrace{\eta_{\mathrm{HE}}}^{c_{hh}}\\ \overbrace{(\eta_{\mathrm{T}}\eta_{\mathrm{C}_a}}^{c_{ea}} & \overbrace{(\eta_{\mathrm{CHP}_e}\eta_{\mathrm{C}_a}}^{c_{ga}} & \overbrace{0}^{c_{ha}} \end{bmatrix} \begin{bmatrix} E_e^{\mathrm{in}}\\ E_g^{\mathrm{in}}\\ E_h^{\mathrm{in}} \end{bmatrix}$$
(28)

Hub #28: it consists of five converters (i.e. transformer, CHCP, heater exchanger, gas furnace, and compressor air) to supply electrical, heat, cool, and compressed air demands by consuming electricity, gas, and heating as follows:

$$\begin{bmatrix} E_e^{\text{out}}\\ E_h^{\text{out}}\\ E_a^{\text{out}}\\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{(1-\nu_2)\eta_{\text{T}}}^{c_{ee}} & \overbrace{\nu_1(1-\nu_2)\eta_{\text{CHCP}_e}}^{c_{ge}} & \overbrace{0}^{c_{he}}\\ \overbrace{\nu_2\eta_{\text{T}}\eta_{\text{C}_h}}^{c_{eh}} & \overbrace{\nu_1\eta_{\text{CHCP}_h} + (1-\nu_1)\eta_{\text{GF}} + \nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_h}}^{c_{hh}} & \overbrace{\eta_{\text{HE}}}^{c_{hh}}\\ \overbrace{\varepsilon_{ec}}^{c_{ec}} & \overbrace{\varepsilon_{gc}}^{c_{gc}} & \overbrace{0}^{c_{hc}}\\ \overbrace{0}^{c_{ea}} & \overbrace{\nu_1\eta_{\text{CHCP}_c}}^{c_{ga}} & \overbrace{0}^{c_{ha}}\\ \overbrace{\nu_2\eta_{\text{T}}\eta_{\text{C}_a}}^{c_{ga}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}}^{c_{ga}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}}^{c_{ga}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}}^{c_{ga}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}}^{c_{ha}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}}^{c_{ha}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}^{c_{ha}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}^{c_{ha}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}^{c_{ha}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{\nu_1\nu_2\eta_{\text{CHCP}_e}\eta_{\text{C}_a}^{c_{ha}} & \overbrace{0}^{c_{ha}}\\ \overbrace{0}^{c_{ha}} & \overbrace{0}^{c_{ha}} \\ \overbrace{0}^{c_{ha}} \\ \overbrace{0}^{c_{ha}} & \overbrace{0}^{c_{ha}} \\ \overbrace{0$$

• Hub #29: it uses transformer, CHP, GF, HE, and compressor air in order to transform electricity, gas, and heating into electricity, heating, and compressed air. The mathematical configuration of this hub can be represented as follows:

$$\begin{bmatrix} E_e^{\text{out}} \\ E_e^{\text{out}} \\ E_a^{\text{out}} \end{bmatrix} = \begin{bmatrix} \overbrace{\nu_{ee}}^{c_{ee}} & \overbrace{\nu_1(1-\nu_2)\eta_{\text{CHP}_e}}^{c_{ge}} & \overbrace{\nu_1(1-\nu_2)\eta_{\text{CHP}_e}}^{c_{he}} & \overbrace{0}^{c_{he}} \\ \overbrace{\nu_2\eta_{\text{T}}\eta_{\text{C}_h}}^{c_{eh}} & \overbrace{\nu_1\eta_{\text{CHP}_h} + (1-\nu_1)\eta_{\text{GF}} + \nu_1\nu_2\eta_{\text{CHP}_e}\eta_{\text{C}_h}}^{c_{he}} & \overbrace{\eta_{\text{HE}}}^{c_{he}} \\ \overbrace{\nu_2\eta_{\text{T}}\eta_{\text{C}_a}}^{c_{ea}} & \overbrace{\nu_1\nu_2\eta_{\text{CHP}_e}\eta_{\text{C}_h}}^{c_{ga}} & \overbrace{0}^{c_{he}} \end{bmatrix} \begin{bmatrix} E_e^{\text{in}} \\ E_g^{\text{in}} \\ E_h^{\text{in}} \end{bmatrix}$$
(30)

Note that, the hub's structures presented in this subsection denote some related structures and do not cover all possible configurations which can be made by transformer, CHP, CHCP, GF, HE, and compressor. Also, considering other hub elements can extend this list.







 E_e^{ot}

 E_h^{\prime}

 $\blacktriangleright E_c^{out}$ $\models E_e^{out}$







E_e^{ou}









Hub #17

Ø

HP

Hub #22

Ø

6

Hub #7

Ø

6)

























3. EHED problem

The problem formulation related to EHED can be stated as an objective function which to be minimized subject to satisfy all equality and inequality constraints. So, in this section, objective function and main constraints are presented.

302 *3.1. Objective function*

303 In this paper, three objective functions are considered as:

304 1) Energy cost minimization (single-objective problem): the energy production cost of all available carriers (i.e. electricity, natural gas, and heating) at the hub input is optimized as (31). The energy 305 306 carriers offered at the input can be seen as energy generators with different cost structures [33]. 307 Note that, considering the valve-point loading effect increases the complexity of the objective function and make it non-smooth and non-convex. Multi-valve steam turbines in large steam 308 309 turbine generators produced a rippling effect on the input-output characteristic which known as "valve-point loading effect" [6]. Thus the generating unit output is not always smooth as shown in 310 311 Fig. 4.

$$OF_{1} = \sum_{i \in \{g,h\}} \sum_{j=1}^{n_{i}} \left(a_{j,i} + b_{j,i} E_{j,i}^{\text{in}} + c_{j,i} \left(E_{j,i}^{\text{in}} \right)^{2} \right) + \sum_{j=1}^{n_{e}} \left(a_{j,e} + b_{j,e} E_{j,e}^{\text{in}} + c_{j,e} \left(E_{j,e}^{\text{in}} \right)^{2} + \left| d_{j,e} \sin \left(e_{j,e} \left(E_{j,e}^{\text{in},\min} - E_{j,e}^{\text{in}} \right) \right) \right| \right)$$
(31)

where $\{a_{j,i}, b_{j,i}, c_{j,i}\}$ are cost coefficients of *j*th source (energy offered at input has been modeled as energy sources) related to *i*th input carrier; also, $e_{j,e}$ and $d_{j,e}$ are the cost coefficients for modeling valve-point effect for electrical carrier; n_i denotes the total number of energy sources associated with *i*th input carrier; $E_{j,i}^{in}$ represents the energy production of *j*th source and *i*th input carrier; and finally, *OF* denotes the objective function.



317 318

Fig. 4. Fuel cost curve with/without valve-point loading effect [6].

Minimization of energy hub losses (single-objective problem): this objective deals with minimizing
 the overall energy losses for all carriers which occurs in all energy hubs. This function reduces the
 differences between the total input and output energies in all hubs as follows:

$$OF_{2} = \sum_{i \in \{e,g,h\}} \sum_{j=1}^{N_{hub}} \left(E_{j,i}^{\text{in}} - E_{i}^{\text{demand}} \right)$$
(32)

- where E_i^{demand} represents the energy demand of the systems for output carrier *i*; and N_{hub} denotes the total number of hubs.
- 3) Minimization of energy cost and hub losses: applying the formulation presented in [16,34], a multi objective problem can be converted to a single-objective problem as follows:

$$OF_3 = OF_1 \left(1 + \frac{OF_2}{\sum_{i \in \{e,g,h\}} E_i^{\text{demand}}} \right)$$
(33)

326 *3.2. Constraints*

- 327 The mentioned optimization problem should be minimized subject to the following constraints:
- Energy flow equation in energy hubs (balance equation of hubs): the general formula (1), which was illustrated in (2)–(30) for different hub structures, shuold be met as below for all hubs in a system:

$$\mathbf{Input}_i = \mathbf{C}_i \mathbf{Output}_i, \ i = 1, \dots, N_{hub}$$
(34)

Energy output of hubs and demand balance: following constraint should be satisfied regarding to
 all hub's output carriers:

$$\sum_{j=1}^{N_{hub}} E_{j,i}^{\text{out}} = E_i^{\text{demand}}, \ i \in \{e, h, c, a\}$$
(35)

Note that, $E_{j,i}^{out} = 0$ if *j*th hub does not have *i*th form of energy at its output.

Capacity limits of all energy units (limitations on hub inputs): for all connected units (heat-only, gas-only, and electric-only ones) to the hubs, following inequality constraint should be investigated:

$$E_{j,i}^{\text{in,min}} \le E_{j,i}^{\text{in}} \le E_{j,i}^{\text{in,max}}, \ i \in \{e, g, h\} \text{ and } j = 1, \dots, n_i$$
 (36)

In this paper, prohibited operating zones are considered for some electric-only units (conventional thermal ones) [35]. This effect could be mainly due to vibration in the shaft bearing caused by the steam valve or faults in the machines themselves or the associated auxiliary equipment, such as boilers and feed pumps [35]. In this condition, the best economy will be achieved when operation in these zones will be avoided. So, prohibited operating zones create disjoint feasible sub-regions and make a non-continuous problem. Hence, the feasible operation of such units can be expressed as follows:

$$E_{j,e}^{\text{in,min}} \leq E_{j,e}^{\text{in,min}_{z_1}} \leq E_{j,e}^{\text{in,min}_{z_1}}$$

$$E_{j,e}^{\text{in,max}_{z_1}} \leq E_{j,e}^{\text{in}} \leq E_{j,e}^{\text{in,min}_{z_2}} \qquad (37)$$

$$E_{j,e}^{\text{in,max}_{z_{i-1}}} \leq E_{j,e}^{\text{in}} \leq E_{j,e}^{\text{in,max}}, \quad i = 1, \dots, n_{zone_j},$$

$$j \in \{\text{Electric units with prohibited zones}\}$$

344 where n_{zone_j} denotes the number of prohibited zones of the *j*th electrical unit; \min_{z_i} and \max_{z_i} 345 are upper and lower bounds on zone *i*th, respectively. Dispatch factor limitation of energy hubs: all dispatch factors related to input or output ports
 should satisfy the following inequality constraint:

 $0 \le \nu \le 1$

348 **4. SAL-TVAC-GSA structure**

349 *4.1. Original GSA structure*

Firstly, Rashedi et al. [36] in 2009 proposed the GSA based on the gravitational law and laws of motion between masses (Newtonian laws). This technique is capable of handling large-scale nonlinear and nonconvex problems as demonstrated in literature [6,34,36–39]. In order to fully understand how this algorithm works, its structure can be represented in the following.

Suppose that there are *N* masses (as *N* agents) and the position of each mass corresponds to a potential solution of the problem. Therefore, the position of the *i*th mass can be defined as follows:

$$X_{i} = \left[x_{i}^{1}, \dots, x_{i}^{d}, \dots, x_{i}^{n}\right]^{T} \quad i = 1, 2, \dots, N$$
(39)

(38)

where x_i^d represents the position of the *i*th mass in the *d*th dimension. $(\cdot)^T$ denotes the transposition of (\cdot) .

Gravity exists everywhere and every particle in the universe attracts the other particles (Fig. 5). The gravitational force between two particles is inversely proportional to the square of the distance between them and directly proportional to the product of their masses. Therefore, the gravitational force between heavier masses with short distance is the highest. Therefore, based on the law of gravity, each mass attracts every other mass and the gravitational force between the *i*th mass because of the *j*th mass in *d*th dimension at specific time *t* is as (40). This is because of the fact that the gravity acts between separated particles without any intermediary and delay [36].

$$F_{ij}^{d} = G(t) \times \frac{M_{i}(t)M_{j}(t)}{R_{ij}(t) + \varepsilon} \times \left(x_{j}^{d}(t) - x_{i}^{d}(t)\right)$$

$$\tag{40}$$

365 with

$$G(t) = G_0 \exp\left(\frac{-\delta t}{\text{Iteration}_{\text{max}}}\right)$$
(41)

$$R_{ij}(t) = \|X_i(t), X_j(t)\|_2$$
(42)

and where G(t) is the gravitational constant which is reduced with time (iteration, age of universe) to control search accuracy [36]. G_0 is the initial value of G(t); Iteration_{max} represents the maximum number of iterations; δ is a constant term; $R_{ij}(t)$ denotes the Euclidian distance between *i*th and *j*th mass;

it is essential to note that according to [6,16,34,36], $R_{ij}(t)$ provides better performance than $R_{ij}^2(t)$ unlike

the law of gravity between two particles.



Fig. 5. The concept of the gravitational force between masses.

The total gravitational force that acts on the *i*th mass in the *d*th dimension is a randomly weighted sum of *d*th components of the forces exerted from other masses as (43).

$$F_i^d(t) = \sum_{\substack{j=1\\ i\neq i}}^N \operatorname{rand}_j \times F_{ij}^d(t)$$
(43)

where rand, denotes a random number in the interval [0, 1].

At the beginning of the optimization process, the reduction of the number of masses with lapse of time in (43) allows the exploration of the space of solutions to avoid trapping in a local optimum. Also, the exploitation power fades with lapse of time. So, a set of agents with heavier masses (K_{best} agents corresponding to good solutions) only apply their gravitational force to the other [36]. K_{best} with initial value K_0 is a function of time which is reduced with the iteration linearly. So, the performance of GSA will be improved by modifying (43) as (44).

$$F_i^d(t) = \sum_{\substack{j \in K_{\text{best}}\\j \neq i}}^N \operatorname{rand}_j \times F_{ij}^d(t)$$
(44)

382 where K_0 is a first set of masses with the best fitness value and heaviest mass which denotes the K_{best} .

The acceleration $a_i^d(t)$ of the *i*th mass at time *t* in dimension *d*, according to the Newton's law of motion is as:

$$a_{i}^{d}(t) = \frac{F_{i}^{d}(t)}{M_{ii}(t)}$$
(45)

where M_{ii} represents the inertial mass of the *i*th agent. Inertial mass denotes the resistance of a mass to change its state of motion when a force is applied [36]. According to this, large inertial masses accelerate more slowly than lighter ones and vice versa [6]. Heavy masses correspond to the better solutions.

- 388 Therefore, they should change their position very little (similar to gbest in PSO) and must attract the other
- solutions which depend on the other masses and distance between them and successively change theirmotions slowly.
- Finally, the (t + 1)th velocity of *i*th mass in the dimension *d* and its updated position can be calculated as (46) and (47), respectively.

$$v_i^d(t+1) = \operatorname{rand}_{1i} \times v_i^d(t) + a_i^d(t)$$
 (46)

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1)$$
(47)

393 The updated mass i in time t may be expressed as follows

$$m_i(t) = \frac{\operatorname{fit}_i(t) - \operatorname{worst}(t)}{\operatorname{best}(t) - \operatorname{worst}(t)}$$
(48)

$$M_{i}(t) = \frac{m_{i}(t)}{\sum_{j=1}^{N} m_{j}(t)}$$
(49)

394 where

$$\operatorname{best}(t) = \min_{j \in \{1, 2, \dots, N\}} \operatorname{fit}_j(t)$$
(50)

$$worst(t) = \max_{j \in \{1,2,\dots,N\}} \operatorname{fit}_{j}(t)$$
(51)

and where fit_{*i*}(t) represents the fitness value of the *i*th mass in time t. In the following section, the presented concepts are employed to form the proposed algorithm.

397 *4.2. Proposed modifications applied to GSA*

In this paper, following modifications are implemented to improve performance of GSA as follows.

399 4.2.1. Calculating gravitational constant based on standard gravitational parameter

400 In the real world, measuring the gravitational constant with high accuracy is difficult while determining 401 standard gravitational parameter, denoted by μ , with acceptable precision is possible. Hence, the 402 parameter $\mu(t)$ at iteration *t*th is calculated by the product of the gravitational constant and sum of two 403 mass *i* and *j* as follows (general representation [40]):

$$\mu(t) = G_0 \times \left(M_i(t) + M_j(t) \right)$$
(52)

404 So, (41) can be modified as follows:

$$G_{ij}(t) = \frac{\mu(t)}{M_i(t) + M_j(t)} \times \exp\left(\frac{-\delta t}{\text{Iteration}_{\text{max}}}\right)$$
(53)

The above equations shows a proper gravitational constant between two specific mass i and j. This is against (41) which assumed a gravitational constant for all masses.

407 In this paper, $\mu(t)$ will be reduced with time to control the search accuracy and provide better 408 performance:

$$\mu(t) = \frac{\xi}{t} \tag{54}$$

409 where ξ is a constant term.

410 4.2.2. A new self-adaptive learning strategy for GSA

- In this strategy, two updating methods are applied in a probabilistic manner to GSA in order to increase its performance. In fact, a more profitable method than other is selected to adaptively give preference to appropriate mutation at each iteration. In this regard, a probability value is assigned to each of the updating methods. This value is dependent on the ability of the corresponding updating method to provide more optimal solutions based on an appropriate adaptively updating mechanism. Two updating methods are as follows:
- 417 *Technique 1*: this method acts as G_{best} -guided in PSO and uses time varying acceleration coefficient as 418 TVAC-PSO [41]. So, (47) is modified as follows:

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) + AC(t) \times \operatorname{rand}_{2i} \times \left(G_{\text{best}} - x_i^d(t)\right), \quad i = 1, \dots, NT_1$$
(55)

419 where

420

$$AC(t) = AC_{\text{initial}} + \frac{AC_{\text{final}} - AC_{\text{initial}}}{\text{Iteration}_{\text{max}}} \times t$$

421 and where *AC* is acceleration coefficient in which AC_{initial} and AC_{final} represent the relevant initial and 422 final values; rand_{2i} is a random number in the interval [0, 1]; *NT*₁ denotes the number of masses which 423 update through Technique 1.

The third term of the right hand side of (47), exploits an exterior memory for obtaining the best solution called G_{best} which obtained from solutions saved until now. To improve the solution quality, AC(t)should be increased at each iteration, i.e. $AC_{\text{final}} > AC_{\text{initial}}$. This is because of the fact that, at the beginning, the high value of AC(t) leads masses to a local optimum prematurely.

428 Note that, by selecting this method, the effect of difference $(G_{\text{best}} - x_i^d(t))$, by applying $AC(t) \times$ 429 rand_{2i}, is implemented which is different from other approaches suggested in literature such as [42,43].

430 *Technique 2*: it is adapted to improve the diversity of the solutions, avoid being trapped in local optima. 431 In this method, five different masses are selected randomly for each mass *i* such that $i \neq i1 \neq i2 \neq i3 \neq$ 432 $i4 \neq i5$. So, a trail solution is calculated as follows [42,43]:

$$x_{i,\text{trail}}^{d}(t+1) = x_{i1}^{d}(t) + \text{rand}_{3i} \times \left(x_{i2}^{d}(t) - x_{i3}^{d}(t)\right) + \text{rand}_{4i} \times \left(x_{i4}^{d}(t) - x_{i5}^{d}(t)\right),$$

$$i = 1, \dots, NT_{2}$$
(56)

- 433 where rand_{3i} and rand_{4i} are two random numbers in the interval [0, 1]; NT_2 denotes the number of 434 masses which update through Technique 2.
- 435 This technique can be identified as follows:

$$x_{i}^{d}(t+1) = \begin{cases} x_{i,\text{trail}}^{d}(t+1) & \text{if } \text{rand}_{5i} \le 0.5 \\ x_{i}^{d}(t+1) & \text{else} \end{cases}$$
(57)

- 436 where rand_{5i} is a random number in the interval [0, 1].
- 437 The probability of both mentioned techniques are calculated as follows [44]:

$$\operatorname{Prob}_{\operatorname{Technique}_{i}} = (1 - \theta) \times \operatorname{Prob}_{\operatorname{Technique}_{i}} + \frac{\theta \times AP_{\operatorname{Technique}_{i}}}{\operatorname{Iteration}_{\max}}, \quad i = 1, 2$$
(58)

438 where θ denotes the learning factor which is selected as $\theta = 0.142$ [42–44]; $AP_{\text{Technique}_i}$ is the 439 accumulator for the *i*th presented technique and can be updated as:

$$AP_{\text{Technique}_i} = AP_{\text{Technique}_i} + wf_j, \qquad j = 1, \dots, NT_i \text{ and } i = 1, 2$$
(59)

440 where wf represents a weight factor for each technique. This factor leads to better solution selection 441 through applying larger weight and can be determined as follows:

$$wf_j = \frac{\log(N - j + 1)}{\log(1) + \dots, \log(N)}, \qquad j = 1, \dots, N$$
 (60)

442 Finally, the normalized probabilities related to each technique are calculated as follows:

$$\operatorname{Prob}_{\operatorname{Technique}_{i}} = \frac{\operatorname{Prob}_{\operatorname{Technique}_{i}}}{\sum_{i=1}^{2} \operatorname{Prob}_{\operatorname{Technique}_{i}}}, \quad i = 1, 2$$
(61)

In summary, this subsection presented two different updating technique based on a probabilistic way. The first technique uses G_{best} applying time varying acceleration coefficient. The second technique is utilized to diverse the solutions through selecting five different masses. In this method, if a random number is larger than 0.5, then conventional updating strategy (47) is selected; else, (57) is used. The selection method for each technique is illustrated in the following section.

448 4.3. Differences between SAL-TVAC-GSA and TVAC-GSA

The main differences between the proposed method and an improved version of GSA, i.e. TVAC-GSA,are summarized as follows:

- In TVAC-GSA only one movement strategy is applied to update positions while in SAL TVAC-GSA three different updating procedures are adopted.
- In SAL-TVAC-GSA, G₀ is calculated based on two involved masses while in TVAC-GSA it is selected at the beginning (in the first step). In other words, in TVAC-GSA, this parameter is constant over all iterations while in SAL-TVAC-GSA it is updated at each iteration (a self-adaptive parameter).
- In SAL-TVAC-GSA, the best movement strategy is used in a probabilistic manner. In fact, a more profitable movement dependent on the ability of the corresponding updating approach to provide a better quality solution is selected.
- In SAL-TVAC-GSA, there is an updating method to diverse the solutions, avoid being trapped
 in local optimum. This method reflects a totally random movement pattern.

462 **5. SAL-TAVC-GSA for EHED problem**

- 463 Solving EHED problem in the form of minimizing (31) or (32) or (33) subject to (34)–(38), will be 464 applied through different steps illustrated in Fig. 6. These steps are expressed as:
- 465 *Step 1*. Initialize the parameters of SAL-TVAC-GSA, i.e. N, K_0 , ξ , δ , $AC_{initial}$, AC_{final} , Iteration_{max}, 466 and initial values of Prob and *AP*.

467 *Step 2.* Set initial control variables as initial positions of all masses within their limits. In the EHED 468 problem, the energy production of all sources and all dispatch factors are independent variables which can 469 be randomly selected within their limits.

470 *Step 3.* Calculate the value of fitness for all masses. In this work, the penalty method to meet all equality constraints has been selected as below:

$$fit = OF_k + W_1 \left(\sum_{i=1}^{N_{hub}} \mathbf{C}_i \mathbf{Output}_i - \mathbf{Input}_i \right)^2 + W_2 \left(\left(E_i^{demand} - \sum_{j=1}^{N_{hub}} E_{j,i}^{out} \right)_{i \in \{e,h,c,a\}} \right)^2, k$$
(48)
= 1, 2, 3

472 where W_1 and W_2 are two weighting factors (penalty parameters). It should be noted that, in order to

- achieve a feasible solution, the weighting factors of the penalty function are increased along the iterativeprocess linearly.
- 475 Step 4. Update $G_{ij}(t)$, best(t), worst(t), and $M_i(t)$ for each set of masses. Also, calculate the total 476 gravitational force using (44) for all agents. Then, determine their acceleration through (45).
- 477 *Step 5.* Calculate velocities using (46).
- 478 *Step 6.* Based on the Roulette Wheel Mechanism (RWM), one of the presented techniques for updating
- the position of each mass should be selected as follows: if Prob_{Technique}, becomes greater than a random
- 480 number in interval [0, 1], then select *Technique 1*; otherwise, select *Technique 2*.
- 481 *Step 7.* Check that all control variables are within their limits. If any of them violates or hits the limit, 482 set it at its limit value (upper or lower).
- 483 Step 8. If the age of algorithm (i.e. iteration) is equal or less than the maximum iteration (i.e. $t \le$ 484 Iteration_{max}), then repeat Step 3–7. Otherwise, go to Step 9.
- 485 *Step 9.* Print the best results.





489 The proposed SAL-TVAC-GSA-based EHED is tested on a new highly nonlinear, non-convex, nonsmooth, non-differential and high-dimensional system with 103 control variables (76 variables for sources 490 and the rest for dispatch factors). Simulation is carried out on this network including 76 sources consist of 491 27 electrical sources with valve-point loading effect (some of them with prohibited operating zones), 34 492 493 gas stations, and 15 heat sources to supply 39 hubs with 29 structures presented in subsection 2.2. The total demand of the networks associated with electricity (i.e. E_e^{demand}), heating (i.e. E_h^{demand}), cooling 494 (i.e. E_c^{demand}), and compressed air (i.e. E_a^{demand}) are 12.0, 9.5, 0.7, and 1.2 pu, respectively. The system 495 data is given in Appendix A. Before go further, it should be mentioned that to test the SAL-TVAC-GSA 496 497 performance, it is evaluated on a set of five benchmark functions and the obtained results are presented in

498 Appendix B.

The suggested method is programmed in MATLAB environment and implemented on an Intel Pentium CPU, 2.0 GHz with 2GB RAM, PC. In order to attain the best quality solution with a good convergence speed, the optimum setting of various SAL-TVAC-GSA parameters should be selected. Hence, different trails for a specific system should be performed to meet the best setting. Accordingly different parameters of SAL-TVAC-GSA are defined as: $\xi = 0.001$, $\delta = 1$, $N = K_0 = 50$, $AC_{\text{initial}} = 0.5$, $AC_{\text{final}} = 1.5$, Iteration_{max} = 200, Prob_{Technique_1} = 0.5, Prob_{Technique_2} = 0.5, $AP_{\text{Technique_1}} = 0$, and

505
$$AP_{\text{Technique}_2} = 0$$

In this section, the best results in terms of quality solution and convergence speed over 30 independent runs are compared with various programmed algorithms such as GA, PSO, GSA, TVAC-GSA, and EGSA (see [42,43]) to illustrate the ability of the proposed algorithm in finding an operating point with lower objective function. Also, all results are in a per-unit (pu) system and all costs are in monetary-unit (mu). It should be noted that, all methods ensure that all constraints are satisfied.

511 6.1. Case 1: Minimization of energy cost as a single-objective problem

512 The obtained optimal solution by the introduced method through minimizing (31) subject to (34)-(38) (or optimizing (48) with k = 1 subject to (36)–(38)) is compared with those that found by TVAC-GSA, 513 EGSA, GSA, PSO and GA in Table 1. This table shows that the optimal operating point searched by the 514 515 proposed technique in terms of quality solution, objective function, and computational time is better than 516 those obtained by all other analyzed approaches. The objective value reached by SAL-TVAC-GSA is 15,728.3913 mu, whereas the optimal values of the objective function searched by TVAC-GSA, EGSA, 517 518 GSA, PSO, and GA approaches are 15,747.3098, 15,751.6029, 15,870.0549, 16,106.0947, and 16,384.4316 mu, respectively. This improvement results in more annual cost saving assuming constant 519 520 load level. Fig. 7 reflects this result and indicates that a little cost improvement can save the annual cost 521 significantly.

522 Based on Table 1, the total energy production obtained by GA, PSO, GSA, EGSA, TVAC-GSA, and the suggested method is 27.4788, 27.1058, 27.9239, 27.0377, 27.0459, and 27.0706 pu, respectively. 523 Also, the total energy losses in hubs obtained by the mentioned techniques are 4.0788, 3.7058, 4.5232, 524 3.6376, 3.6459, and 3.6706 pu, respectively. Moreover, the proposed method with about 17.2 seconds is 525 526 faster than all other techniques. This shows about 9% time saving (average). Fig. 8 illustrates dispatch 527 factors related to the input and output of all hubs obtained by SAL-TVAC-GSA. It can be easily seen that 528 these variables are in their acceptable ranges. Finally, Fig. 9 represents the convergence characteristic 529 curves of all analyzed algorithms.





Table 1. Comparative results using different techniques-energy cost minimization

	Energy	Optimal Production (pu)							
Hub Code	Hub Type	Туре	GA	PSO	GSA	EGSA	TVAC-GSA	SAL-TVAC-GSA	
A1	#1	Electricity	0.1000	0.1000	0.1000	0.1020	0.1000	0.1003	
A2	#1	Electricity	0.4000	0.4000	0.4037	0.4072	0.4003	0.4041	
B1	#2	Gas	0.5000	0.5000	0.5000	0.5014	0.5003	0.5001	
C1	#3	Gas	1.8984	0.3044	0.3417	0.3515	0.3227	0.3522	
D1	#4	Gas	0.1345	0.9610	0.5993	0.5742	0.6367	0.5865	
E1	#5	Heat	0.3636	0.2000	0.2000	0.2000	0.2013	0.2007	
171	#6	Electricity	0.2000	0.2000	0.2000	0.2000	0.2001	0.2000	
FI	#0	Gas	0.1000	0.4255	0.1079	0.1068	0.1040	0.1074	
F2	#6	Electricity	0.3000	0.3000	0.3007	0.3042	0.3027	0.3036	
12	#0	Gas	1.3382	0.9565	1.0583	1.1857	1.0078	1.1092	
G1	#7	Electricity	0.8493	0.1000	0.8663	0.8663	0.8693	0.8744	
Ш1	#8	Electricity	0.2000	1.5000	0.2391	0.2280	0.2127	0.2304	
пі	#0	Gas	0.3655	0.3285	0.2000	0.2007	0.2009	0.2002	
I1	#9	Gas	0.1500	0.1500	0.1739	0.1721	0.1762	0.1721	
T1	#10	Gas	0.1000	0.1000	0.1944	0.1867	0.1959	0.2236	
31	#10	Heat	0.2000	0.2014	0.2000	0.2062	0.2030	0.2039	
K1	#11	Gas	0.1000	0.1000	0.1239	0.1178	0.1189	0.1303	
KI	#11	Heat	0.2001	0.2000	0.2000	0.2001	0.2007	0.2000	
L1	#12	Gas	0.3000	0.3000	0.3001	0.3001	0.3003	0.3000	
M1	#13	Electricity	0.1010	0.1000	0.1096	0.1239	0.1106	0.1169	
1011	#15	Heat	0.1000	0.1000	0.4888	0.4950	0.4683	0.4646	
N1	#14	Electricity	0.1000	0.1000	0.1021	0.1030	0.1005	0.1002	
111		Gas	1.1255	0.2000	1.5872	1.5831	1.6168	1.5558	
01	#15	Gas	0.3308	0.4976	0.5486	0.5300	0.5230	0.5023	
01	#15	Heat	0.1000	0.1000	0.1000	0.1021	0.1003	0.1002	
P1	#16	Gas	0.1000	0.1064	0.3465	0.3121	0.3438	0.3315	
Q1	#17	Gas	0.1000	0.2240	0.4303	0.4546	0.4830	0.4109	
Q2	#17	Gas	0.7447	0.2000	0.2091	0.2105	0.2086	0.2139	
		Electricity	0.3000	1.5911	1.6375	1.6053	1.6101	1.6092	
R1	#18	Gas	0.1243	0.1000	0.1000	0.1001	0.1010	0.1001	
		Heat	0.1879	0.1000	0.2154	0.1887	0.2086	0.2074	
~ .		Electricity	0.2000	0.2000	0.2000	0.2046	0.2001	0.2010	
S1	#19	Gas	0.2000	0.2000	0.2012	0.2004	0.2031	0.2007	
		Heat	0.3137	0.7000	0.1977	0.2138	0.1999	0.1895	
62		Electricity	2.1000	0.1000	0.8861	0.8939	0.8934	0.8859	
52	#19	Gas	0.1000	0.1000	0.1141	0.11//	0.1058	0.1108	
		Heat	0.9000	0.1000	0.1112	0.1113	0.1121	0.11/2	
62	#10	Electricity	0.1000	0.1000	0.1000	0.1009	0.1000	0.1000	
55	#19	Uas	0.1000	0.1000	0.1997	0.1970	0.2450	0.2190	
		пеат	0.1000	0.1000	0.1000	0.1015	0.1001	0.1005	

T 1	#20	Electricity	0.7133	0.1000	0.1230	0.1192	0.1220	0.1175
11	#20	Gas	0.5701	0.3000	0.3000	0.3080	0.3007	0.3013
T7	#20	Electricity	0.2107	0.1000	0.1000	0.1000	0.1002	0.1003
12	#20	Gas	0.3737	0.3000	0.3059	0.3066	0.3076	0.3065
TT1	#21	Electricity	0.1000	0.1000	0.8999	0.9116	0.8834	0.9017
01	#21	Gas	0.3000	0.3000	0.3000	0.3013	0.3000	0.3000
V1	#22	Electricity	0.2000	0.2000	0.2000	0.2022	0.2005	0.2000
V I	#22	Gas	0.1000	1.3834	0.9573	0.9861	0.9623	0.9591
3371	#22	Electricity	0.1000	0.1000	0.1082	0.1050	0.1095	0.1050
W I	#23	Gas	1.9000	1.9000	0.9181	0.8540	0.9353	0.9435
WO	#22	Electricity	0.3000	0.3000	0.3000	0.3000	0.3026	0.3008
w2	#23	Gas	0.1000	1.4000	0.9821	0.9523	0.9859	0.9834
X/1	112.4	Electricity	0.2000	0.9115	0.2000	0.2001	0.2003	0.2015
AI	#24	Gas	0.2000	0.3930	0.2035	0.2002	0.2015	0.2049
V1	#25	Electricity	2.5839	3.0000	2.7226	2.7053	2.7542	2.7001
Y I	#25	Gas	0.1000	0.1000	0.9821	0.1000	0.1001	0.1001
NO.	#25	Electricity	0.5004	0.0000	0.0153	0.0175	0.0111	0.0137
Y Z	#25	Gas	0.1000	0.1454	0.1191	0.1159	0.1214	0.1238
		Electricity	0.1000	0.1000	0.1000	0.1004	0.1015	0.1016
Z1	#26	Gas	0.1000	0.1936	0.1128	0.1182	0.1238	0.1187
		Heat	0.1097	0.1000	0.4355	0.4475	0.4522	0.4735
		Electricity	0.2001	0.2000	0.2000	0.2000	0.2010	0.2051
Γ1	#27	Gas	0.2000	0.2000	0.2000	0.2001	0.2000	0.2001
		Heat	0.1000	0.3338	0.1045	0.1004	0.1001	0.1023
		Electricity	0.1000	0.1000	0.1000	0.1000	0.1001	0.1002
Г2	#27	Gas	0.2074	0.2000	0.2834	0.2864	0.2355	0.3007
		Heat	0.2540	0.2000	0.2003	0.2003	0.2007	0.2021
		Electricity	0.9000	0.9000	0.8268	0.8303	0.8268	0.8269
Ψ1	#28	Gas	0.1000	0.1000	0.1407	0.1460	0.1428	0.1324
		Heat	0.2000	0.2000	0.2000	0.2015	0.2003	0.2003
		Electricity	0.1000	0.1000	0.1354	0.1359	0.1350	0.1313
Σ1	#29	Gas	0.1000	0.1000	0.1481	0.1400	0.1438	0.1455
		Heat	0.1004	0.1000	0.2138	0.2083	0.2124	0.2095
		Electricity	0.2000	0.2000	0.2000	0.2018	0.2001	0.2000
Σ2	#29	Gas	0.3276	0.1000	0.1859	0.1722	0.1764	0.2150
		Heat	0.1000	0.1987	0.1045	0.1029	0.1067	0.1061
		Electricity	11.4587	11.2026	11.3763	11.3686	11.3481	11.3315
Total Production (pu)		Gas	12.6907	12.9693	13.4752	12.5897	12.6313	12.6614
Heat		3.3294	2.9339	3.0717	3.0794	3.0665	3.0777	
Total Losses (pu)			4.0788	3.7058	4.5232	3.6376	3.6459	3.6706
Cost (mu)			16384.4316	16106.0947	15870.0549	15751.6029	15747.3098	15728.3913
Objective Function (mu)			16384.4316	16106.0947	15870.0549	15751.6029	15747.3098	15728.3913
Computatio	Computational Time (s)			18.5038	17.3926	17.2627	17.3030	17.2354



Fig. 8. Dispatch factors of all hubs obtained by SAL-TVAC-GSA for energy cost minimization









537 In the analyzed system, hub code T1 with hub type #20 is selected to show how energy is consumed, 538 converted, and finally delivered to the loads. This hub is depicted in Fig. 10. According to the obtained 539 results of SAL-TVAC-GSA, this hub consumes 0.1175 and 0.3013 pu electricity and gas, respectively. 540 These values are 1.03 and 2.37% of total electricity and gas generations, respectively. Based on optimal dispatch factor v = 62.819%, 0.1893 pu of the entire gas is used by CHP unit and the rest is consumed 541 by gas furnace. The entire electricity is completely delivered to transformer. After energy conversion by 542 the mentioned elements, two types of energy, i.e. electricity and heat, are available at the output. CHP 543 generates 0.0663 pu electrical power which is added to 0.1175 pu to supply 1.53% of total electrical 544 demand. Moreover, the produced heat by gas furnace (0.0728 pu) and CHP (0.0852 pu) supplies 1.66% of 545 546 total heat demand. Meanwhile, the hub loss is 0.0770 pu (2.09% of total energy losses) and the energy 547 cost of this hub is 171.3114 mu (1.09% of total energy cost).



Fig. 10. Energy conversion of hub code T1 (hub type #20) based on results of SAL-TVAC-GSA in Case 1

551 6.2. Case 2: Minimization of energy losses as a single-objective problem

The aim of this subsection is to minimize (32) subject to (34)–(38) (or optimize (48) with k = 2 subject 552 553 to (36)-(38)). The obtained results by SAL-TVAC-GSA in terms of optimal energy production (along 554 with total electricity, gas, and heat generations), total losses (as the objective function), energy cost, as 555 well as computational time are compared with those found by TVAC-GSA, EGSA, GSA, PSO, and GA 556 in Table 2. Moreover, Fig. 11 reflects dispatch factors of all hubs related to SAL-TVAC-GSA solution. It 557 can be seen that, the proposed algorithm can reach to a better quality solution with lower losses and CPU 558 time. The energy cost searched by SAL-TVAC-GSA, TVAC-GSA, EGSA, GSA, PSO, and GA are about 16825, 16811, 16824, 17308, 16858, and 16623 mu, respectively. In this viewpoint, the proposed 559 560 approach results in about 1.2% increasing in the energy cost. It is because of the fact that in this case, the 561 energy cost is not important (it is not included in the objective function). Moreover, the energy losses 562 found by the mentioned techniques are 2.8100, 2.8317, 2.8162, 2.9385, 2.9950, and 3.3902 pu, 563 respectively. Average computational time improvement is about 16.9 seconds. Also, total energy 564 productions obtained by the mentioned algorithms are 26.2100, 26.2369, 26.2162, 26.3385, 26.3950, and 26.7902 pu, respectively. It is clear that based on (32) this type of problem should search a lower energy 565 566 production level. Convergence characteristic curves of all tested algorithms are shown in Fig. 12.

Table 2. Con	parative resul	ts using diff	ferent	techni	iques	ener	gy	loss	minin	nization	
				· ·	1 D		•				1

		Energy	Optimal Prod	Optimal Production (pu)								
Hub Code	ode Hub Type Type	Туре	GA	PSO	GSA	EGSA	TVAC-GSA	SAL-TVAC-GSA				
A1	#1	Electricity	0.1679	0.1031	0.7438	0.7469	0.7500	0.7498				
A2	#1	Electricity	0.4818	0.4000	0.4000	0.4000	0.4000	0.4002				
B1	#2	Gas	0.5075	0.5000	0.5026	0.5000	0.5006	0.5000				
C1	#3	Gas	0.3521	0.8796	0.3656	0.3000	0.3000	0.3000				
D1	#4	Gas	0.1622	0.1000	0.1295	0.1000	0.1001	0.1000				
E1	#5	Heat	0.2405	0.2167	0.2044	0.5000	0.5000	0.4999				
F1	#6	Electricity	0.2408	0.9331	0.2000	1.2500	1.2500	1.2500				
ГІ	#0	Gas	0.1125	0.1144	0.1111	0.1000	0.1000	0.1000				
E2	#6	Electricity	0.3539	1.7404	1.7500	0.3007	0.3006	0.3000				
1.7	#0	Gas	0.2384	0.1000	0.4655	1.4000	1.4000	1.4000				
G1	#7	Electricity	0.8798	0.9991	0.1039	0.1080	0.1040	0.1087				
U 1	#9	Electricity	1.1270	0.2006	0.5254	0.2000	0.2000	0.2000				
пі	HI #8	Gas	0.2229	0.2000	0.2058	0.2240	0.2336	0.2231				
I1	#9	Gas	0.3219	0.1947	0.2693	0.1500	0.1500	0.1502				
11	#10	Gas	0.3349	1.0234	0.3984	0.1958	0.2703	0.1936				
J1 #10	π10	Heat	0.2086	0.3184	0.4702	0.4996	0.4995	0.4991				

17.1		Gas	0.3239	0.1000	0.3549	0.1001	0.1000	0.1000
KI	#11	Heat	0.2074	0.5000	0.2747	0.2000	0.2000	0.2000
L1	#12	Gas	0.3679	1.1099	0.8512	0.3000	0.3001	0.3000
		Electricity	0.2369	0.7270	0.7500	0.2766	0.2761	0.2778
M1	#13	Heat	0.6043	0.7630	0.3299	0.1000	0.1001	0.1001
		Electricity	0.1001	0.7500	0.1073	0.1593	0.1513	0.1562
N1	#14	Gas	1.8186	0.3733	0.2094	0.2000	0.2004	0.2000
		Gas	0.3066	0.1000	0.1117	0.1000	0.1000	0.1000
01	#15	Heat	0.1615	0.3216	0.1076	0.1000	0.1000	0.1000
P1	#16	Gas	0.3291	0.1000	0.5329	0.1321	0.1358	0.1311
01	#17	Gas	0.1422	0.1000	0.1027	0.1000	0.1000	0.1000
02	#17	Gas	0.2268	0.2022	0.2000	0.2000	0.2000	0.2000
		Electricity	0.9549	0.9981	0.3995	1.7500	1 7497	1.7500
R1	#18	Gas	0.1905	0.1000	0.1000	1.0965	1.0879	1.0981
		Heat	0.3347	0.2465	0.8812	0.9000	0.8996	0.9000
		Electricity	0.7789	0.2080	0.7807	1.0988	1.1000	1.0995
S1	#19	Gas	0.2432	0.2000	0.2521	0.2001	0.2002	0.2000
		Heat	0.2749	0.7000	0.6309	0.4517	0.4525	0.4611
		Electricity	0.8853	0.8884	0.1374	0.1002	0.1000	0.1000
S2	#19	Gas	0.2036	0.1000	0.1019	0.1000	0.1000	0.1000
		Heat	0.1386	0.1000	0.1003	0.1000	0.1001	0.1000
		Electricity	0.1086	0.1385	0.1712	0.1000	0.1000	0.1000
S 3	#19	Gas	0.1274	0.1000	0.1000	0.1000	0.1000	0.1000
		Heat	0.1053	0.2451	0.1256	0.1000	0.1000	0.1000
т1	#20	Electricity	0.1259	0.1000	0.7500	0.7500	0.7499	0.7499
11	#20	Gas	0.3594	0.3030	0.3520	0.3000	0.3003	0.3000
т2	#20	Electricity	0.1577	0.1016	0.2794	0.1000	0.1000	0.1000
12	#20	Gas	0.3789	0.3000	0.3156	0.3351	0.3178	0.3325
111	#21	Electricity	1.4026	0.3015	1.1662	0.1000	0.1000	0.1002
01	1121	Gas	0.3002	0.3000	0.3053	0.3005	0.3001	0.3000
V1	#22	Electricity	0.2024	0.2862	0.2729	0.2367	0.2174	0.2431
		Gas	0.4828	0.1000	0.1261	0.1001	0.1000	0.1000
W1	#23	Electricity	0.1112	0.1309	0.1000	0.7500	0.7500	0.7500
		Gas	0.6799	0.2085	0.2184	0.2143	0.2095	0.2032
W2	#23	Electricity	0.3016	0.7974	0.3000	0.3002	0.3000	0.3000
		Gas	0.9461	0.1907	0.7903	1.4000	1.4000	1.4000
X1	#24	Electricity	0.2000	0.2378	0.2000	0.2000	0.2000	0.2000
		Gas	0.2634	0.2000	0.2096	0.2000	0.2000	0.2000
Y1	#25	Electricity	0.9540	0.0027	0.0000	0.0000	0.0000	0.0000
		Gas	0.1022	0.1000	0.1007	0.1000	0.1000	0.1000
Y2	#25	Electricity	0.0688	0.2005	0.2919	0.0000	0.0000	0.0000
		Gas	0.1327	0.1000	0.4514	0.1000	0.1002	0.1001
71	#26	Electricity	0.1572	0.1000	0.2022	0.1000	0.1000	0.1000
ZI	#20	Gas	0.1000	0.7308	0.1179	0.1001	0.1000	0.1000
		Flootrigity	0.2313	0.2140	0.1000	0.1000	0.1000	0.1000
Г1	#27	Gas	0.2727	0.2149	0.9071	0.2000	0.2000	0.2000
11	<i>π∠1</i>	Heat	0.2320	0.1403	0.2000	0.2000	0.2000	0.2000
		Flectricity	0.1034	0.1000	0.1000	1 1000	1 1000	1 1000
Γ2	#27	Gas	0.4075	0.2000	0.3258	0.2000	0.2002	0.2000
12		Heat	0.2049	0.2000	0.2015	0.2000	0.2000	0.2000
		Electricity	0.9000	0.8976	0.0565	0.9000	0,9000	0.8995
Ψ1	#28	Gas	0.1387	0.1000	0.1000	0.1000	0.1000	0.1000
		Heat	0.2078	0.2050	0.2000	0.2000	0.2000	0.2000
		Electricity	0.2239	0.1000	0.1427	0.1000	0.1000	0.1000
Σ1	#29	Gas	0.2067	0.3161	0.4159	0.1000	0.1000	0.1000
		Heat	0.2051	0.1161	0.3412	0.1409	0.1263	0.1374
		Electricity	0.2018	0.2000	1.0805	0.5479	0.5512	0.5454
Σ2	#29	Gas	0.1252	0.1183	0.1811	0.1000	0.1000	0.1000
		Heat	0.4228	0.6746	0.3709	0.8000	0.8000	0.8000
		Electricity	11.6991	11.8574	11.9186	11.8753	11.8555	11.8803
Total Produc	ction (pu)	Gas	11.4085	9.7112	9.5815	9.4488	9.5035	9.4320
		Heat	3.6826	4.8264	4.8384	4.8922	4.8779	4.8977
		<i>.</i>						

Total Losses (pu)	3.3902	2.9950	2.9385	2.8162	2.8317	2.8100
Cost (mu)	16622.8797	16858.0050	17308.0887	16823.5307	16811.3114	16824.7134
Objective Function (pu)	3.3902	2.9950	2.9385	2.8162	2.8317	2.8100
Computational Time (s)	17.2353	11.7354	9.9919	9.6391	9.5825	9.2078









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573 6.3. Case 3: Minimization of energy cost and losses simultaneously as a multi-objective problem

In order to demonstrate the effectiveness of the proposed SAL-TVAC-GSA to solve multi-objective problems, energy cost and hub losses are optimized simultaneously. For this purpose, minimizing (33) subject to (34)–(38) (or optimizing (48) with k = 3 subject to (36)–(38)) is investigated. The optimal values of energy production and objective function related to the suggested technique and TVAC-GSA, EGSA, GSA, PSO, and GA are tabulated in Table 3. Moreover, total production of each carrier, total energy cost and losses, as well as computational time of the mentioned algorithms are illustrated in this table. It can be observed that when energy cost along with energy loss is simultaneously minimized, the 581 objective function value obtained by the proposed algorithm is about 18169 mu, whereas the optimal values of objective function searched by TVAC-GSA, EGSA, GSA, PSO, and GA approaches are about 582 18199, 18188, 18273, 18588, and 18960 mu, respectively. Moreover, the suggested approach provides a 583 584 lower energy cost and computational time if compared with all other presented algorithms. In fact, the 585 obtained energy costs by the mentioned algorithms are about 15730, 15752, 15755, 15965, 16402, and 16389 mu, respectively. Also, the average computational time is about 20.7 seconds while for the GSA 586 587 family (i.e. GSA, EGSA, TVAC-GSA, and SAL-TVAC-GSA) it is about 18.7 seconds. Theses mean that employing different versions of GSA leads to the better results in terms of both quality solution and 588 computational time. Moreover, these clearly indicate that SAL-TVAC-GSA outperforms the other 589 590 presented techniques. The average annual cost saving assuming constant load level is about 2820855 mu 591 for about 2% cost improvement. This indicates that a little cost improvement can significantly save the 592 cost. Consequently, discrimination for real-life applications should be done on the basis of searching the better results, i.e. the capability to provide a better quality solution considering economical benefits 593 594 without convergence problems. The optimal values of dispatch factors of all hubs related to SAL-TVAC-GSA solution are illustrated in Fig. 13. Furthermore, convergence curves of all analyzed algorithms are 595 596 depicted in Fig. 14.

		Energy	Optimal Production (pu)								
Hub Code	Hub Type	Туре	GA	PSO	GSA	EGSA	TVAC-GSA	SAL-TVAC-GSA			
A1	#1	Electricity	0.1244	0.1000	0.1014	0.1000	0.1000	0.1005			
A2	#1	Electricity	0.4153	0.4000	0.4000	0.4038	0.4035	0.4000			
B1	#2	Gas	0.5474	0.5000	0.5013	0.5002	0.5000	0.5069			
C1	#3	Gas	0.3291	0.4001	0.4368	0.3266	0.3421	0.3428			
D1	#4	Gas	0.3409	0.1000	0.5094	0.6481	0.6036	0.5939			
E1	#5	Heat	0.2000	0.2141	0.2112	0.2010	0.2002	0.2000			
E1	#6	Electricity	0.2835	0.2103	0.2006	0.2000	0.2004	0.2020			
ГІ	#0	Gas	0.1465	0.8476	0.1000	0.1000	0.1082	0.1160			
E2	#6	Electricity	0.3011	0.3001	0.3062	0.3067	0.3003	0.3000			
1.2	#0	Gas	0.7551	0.1000	0.9249	1.0361	1.0619	1.0597			
G1	#7	Electricity	0.8985	1.0000	0.9158	0.8754	0.8663	0.8639			
H1	#8	Electricity	0.8241	0.3302	0.2689	0.2294	0.2387	0.2437			
111	#0	Gas	0.3768	0.2795	0.2467	0.2000	0.2000	0.2000			
I1	#9	Gas	0.1603	0.4000	0.2326	0.1728	0.1740	0.1759			
T1	#10	Gas	0.1975	1.0955	0.1861	0.1864	0.1947	0.2028			
51	#10	Heat	0.2420	0.4942	0.2000	0.2000	0.2000	0.2000			
К1	#11	Gas	0.2616	0.1992	0.1002	0.1241	0.1241	0.1256			
IXI	"11	Heat	0.3244	0.2573	0.2000	0.2044	0.2000	0.2025			
L1	#12	Gas	0.4642	0.3306	0.3574	0.3076	0.3008	0.3017			
M1	#13	Electricity	0.1281	0.1000	0.1375	0.1105	0.1094	0.1134			
	115	Heat	0.2775	0.2843	0.6157	0.5015	0.4842	0.5010			
N1	#14	Electricity	0.1161	0.7461	0.1016	0.1014	0.1018	0.1007			
		Gas	1.6102	0.2000	1.8983	1.5933	1.5857	1.5754			
01	#15	Gas	0.1895	0.1247	0.1192	0.5379	0.5502	0.5193			
		Heat	0.1629	0.1000	0.1181	0.1000	0.1000	0.1001			
P1	#16	Gas	0.3313	0.1082	0.1584	0.3584	0.3447	0.3567			
Q1	#17	Gas	0.2369	0.1000	0.1132	0.4241	0.4272	0.4599			
Q2	#17	Gas	0.2031	0.3594	0.2293	0.2088	0.2088	0.2063			
		Electricity	0.9708	0.3017	1.5679	1.6297	1.6330	1.6095			
R1	#18	Gas	0.1044	0.1530	0.1028	0.1022	0.1000	0.1001			
		Heat	0.1296	0.1983	0.1887	0.2205	0.2220	0.2167			
		Electricity	0.3742	1.1000	0.2000	0.2009	0.2000	0.2000			
51	#19	Gas	0.2033	0.3708	0.2012	0.2015	0.2016	0.2052			
		Heat	0.1629	0.5709	0.1297	0.2047	0.2008	0.2103			
S2	#19	Electricity	1.6643	0.1005	1.6880	0.8912	0.8868	0.8854			
52		Gas	0.1087	0.1088	0.1211	0.1142	0.1128	0.1116			

Table 3. Comparative results using different techniques-minimization of energy cost and losses

		Heat	0.1207	0.9000	0.1186	0.1136	0.1005	0.1178
		Electricity	0.1023	0.1072	0.1034	0.1000	0.1000	0.1000
S3	#19	Gas	0.1525	0.1509	0.2581	0.2201	0.1989	0.2431
		Heat	0.1431	0.1331	0.1411	0.1001	0.1000	0.1034
T1	#20	Electricity	0.1566	0.1574	0.1439	0.1217	0.1219	0.1249
11	#20	Gas	0.3528	0.4338	0.3433	0.3001	0.3002	0.3001
T	#20	Electricity	0.1892	0.1000	0.1082	0.1019	0.1001	0.1001
12	#20	Gas	0.5529	0.3000	0.3274	0.3071	0.3057	0.3095
TT1	#21	Electricity	0.1914	0.1026	0.9612	0.9232	0.9027	0.9056
01	#21	Gas	0.3819	0.3001	0.3000	0.3013	0.3004	0.3000
¥71	#22	Electricity	0.2033	0.3709	0.2065	0.2000	0.2001	0.2003
V I	#22	Gas	0.7376	0.1000	1.0649	0.9448	0.9575	0.9482
W/1	#22	Electricity	0.1409	0.1007	0.1066	0.1128	0.1103	0.1000
VV 1	#23	Gas	0.7607	0.6472	0.5136	0.9012	0.9099	0.9148
W2	#23	Electricity	0.3162	1.6813	0.3000	0.3001	0.3000	0.3000
VV 2	π23	Gas	1.1029	0.1032	1.3347	0.9721	0.9755	0.9619
V 1	#24	Electricity	0.2627	0.2000	0.2054	0.2003	0.2001	0.2010
ЛІ	<i>π2</i> 4	Gas	0.3442	0.6816	0.2549	0.2051	0.2040	0.2008
V 1	#25	Electricity	1.8365	2.8261	1.8909	2.7042	2.7292	2.6978
11	π23	Gas	0.1222	0.3547	0.1269	0.1002	0.1002	0.1001
V2	#25	Electricity	0.3167	0.0073	0.0020	0.0171	0.0154	0.0127
12	#23	Gas	0.2425	0.1000	0.2459	0.1179	0.1189	0.1208
		Electricity	0.1000	0.1000	0.1047	0.1000	0.1000	0.1000
Z1	#26	Gas	0.2979	0.1000	0.1238	0.1087	0.1129	0.1112
		Heat	0.2016	0.1674	0.2044	0.4289	0.4334	0.4009
		Electricity	0.2008	0.2000	0.2103	0.2006	0.2000	0.2003
Γ1	#27	Gas	0.2061	0.2290	0.2168	0.2000	0.2002	0.2000
		Heat	0.1511	0.1370	0.1108	0.1001	0.1043	0.1097
		Electricity	0.1103	0.1015	0.1000	0.1009	0.1000	0.1009
Г2	#27	Gas	0.2507	0.2000	0.2261	0.2754	0.2833	0.2228
		Heat	0.2965	0.2269	0.2311	0.2000	0.2001	0.2000
		Electricity	0.8146	0.0117	0.8292	0.8269	0.8267	0.8268
Ψ1	#28	Gas	0.1544	0.4013	0.1552	0.1417	0.1414	0.1434
		Heat	0.2000	0.2073	0.2084	0.2000	0.2000	0.2000
		Electricity	0.2441	0.5676	0.1708	0.1356	0.1362	0.1635
Σ1	#29	Gas	0.2358	0.6163	0.1401	0.1051	0.1478	0.1452
		Heat	0.2224	0.3984	0.1533	0.2203	0.2117	0.2130
50	1120	Electricity	0.2036	0.2110	0.2201	0.2000	0.2000	0.2026
Σ2	#29	Gas	0.1860	0.1000	0.1046	0.1779	0.1839	0.2156
			0.1000	0.1001	0.1209	0.1030	0.1049	0.1001
Electricity		11.4896	11.5342	11.3311	11.3944	11.3830	11.3333	
Total Produ	ction (pu)	Gas	12.6479	10.5955	12.2752	12.5209	12.5809	12.5976
Heat		2.9347	4.3893	2.9580	3.1001	3.0721	3.0754	
Total Losse	s (pu)		3.6722	3.1190	3.3843	3.6154	3.6360	3.6284
Cost (mu)			16388.6511	16402.3627	15964.8911	15754.6403	15751.8705	15730.4677
Objective F	unction (mu)		18960.5487	18588.6434	18273.8646	18188.8198	18199.4468	18169.6515
Computational Time (s)		29.6453	19.6453	18.8789	18.8837	18.6678	18.5632	



Fig. 13. Dispatch factors of all hubs obtained by SAL-TVAC-GSA for minimization of energy cost and losses





601 **7. Conclusion**

In this paper, SAL-TVAC-GSA as a new and powerful version of GSA was proposed to solve both 602 603 single- and multi-objective EHED problems. Applying three fundamental modifications to GSA change it 604 to a powerful optimization algorithm which can handle and optimize highly nonlinear, non-convex, non-605 smooth, non-differential, and high-dimensional EHED problems. Furthermore, a new structure for EHED 606 was proposed and a new complex system including various hubs with different elements and structures was introduced. Moreover, valve-point loading effect for all electrical power-only units and prohibited 607 608 operating zones for some of them are considered in the problem formulation. For optimization purpose, three cases are optimized as: the first two cases were minimized energy cost and energy hub losses as two 609 different single-objective EHED problems respectively and the final case was simultaneously considered 610 minimization of energy cost and hub losses as a new multi-objective problem. The obtained results using 611 SAL-TVAC-GSA were compared with those found by TVAC-GSA, EGSA, GSA, PSO, and GA 612 613 techniques. The comparative results demonstrated that the proposed algorithm can search better quality solution with good convergence characteristics and a computational time fully compatible with 614

operational planning time requirements. The other main advantages of the introduced algorithm are its

simplicity of implementation, accuracy and fast convergence to the optimal solution while satisfying all

617 constraints. Moreover, the robustness of the proposed algorithm was tested on five benchmark functions.

618 The obtained results were compared with different well-known techniques and the comparison showed

619 that the proposed SAL-TVAC-GSA gives better results. Considering energy networks and the relevant

620 constraints could be investigated in future research works.

621 622

Appendix A

System Data

The under studied system includes 76 sources (electrical, gas, and heat units). Moreover, 39 hubs with
29 different configurations (see Fig. 3) construct this system. Characteristics of this system are tabulated
as Table A.1–A.4.

Table A.1. H	lub data	
Hub Code	Hub Type	Efficiency
A1	#1	$\eta_{\rm T} = 0.99$
A2	#1	$\eta_{\mathrm{T}} = 1.00$
B1	#2	$\eta_{\text{CHP}_{e}} = 0.30, \eta_{\text{CHP}_{h}} = 0.40$
C1	#3	$\eta_{\text{CHCP}_e} = 0.25, \eta_{\text{CHCP}_h} = 0.35, \eta_{\text{CHCP}_c} = 0.20$
D1	#4	$\eta_{\mathrm{GF}} = 0.75$
E1	#5	$\eta_{\rm HE}=0.95$
F1	#6	$\eta_{\rm T} = 1.00, \eta_{\rm CHP_e} = 0.27, \eta_{\rm CHP_h} = 0.41$
F2	#6	$\eta_{\rm T} = 0.98, \eta_{\rm CHP_e} = 0.31, \eta_{\rm CHP_h} = 0.42$
G1	#7	$\eta_{\rm T} = 1.00, \eta_{\rm Ca} = 0.70, \eta_{\rm Ch} = 0.20$
H1	#8	$\eta_{\rm T} = 0.98, \eta_{\rm CHCP_e} = 0.27, \eta_{\rm CHCP_h} = 0.37, \eta_{\rm CHCP_c} = 0.20$
I1	#9	$\eta_{\rm GF} = 0.80, \eta_{\rm CHP_e} = 0.31, \eta_{\rm CHP_h} = 0.38$
J1	#10	$\eta_{\rm HE} = 0.98, \eta_{\rm CHP_e} = 0.30, \eta_{\rm CHP_h} = 0.42$
K1	#11	$\eta_{\rm HE} = 0.95, \eta_{\rm CHCP_e} = 0.25, \eta_{\rm CHCP_h} = 0.30, \eta_{\rm CHCP_c} = 0.30$
L1	#12	$\eta_{\rm GF} = 0.70, \eta_{\rm CHCP_e} = 0.29, \eta_{\rm CHCP_h} = 0.35, \eta_{\rm CHCP_c} = 0.24$
M1	#13	$\eta_{\rm T} = 0.98, \eta_{\rm HE} = 0.90$
N1	#14	$\eta_{\rm T} = 0.95, \eta_{\rm GF} = 0.73$
01	#15	$\eta_{\rm HE} = 0.90, \eta_{\rm GF} = 0.75$
P1	#16	$\eta_{\text{CHCP}_e} = 0.30, \eta_{\text{CHCP}_h} = 0.31, \eta_{\text{CHCP}_c} = 0.29, \eta_{\text{C}_a} = 0.7, \eta_{\text{C}_h} = 0.20$
Q1	#17	$\eta_{\text{CHP}_e} = 0.30, \eta_{\text{CHP}_h} = 0.40, \eta_{\text{C}_a} = 0.70, \eta_{\text{C}_h} = 0.20$
Q2	#17	$\eta_{\text{CHP}_e} = 0.35, \eta_{\text{CHP}_h} = 0.35, \eta_{\text{C}_a} = 0.65, \eta_{\text{C}_h} = 0.23$
R1	#18	$\eta_{\rm T} = 1.00, \eta_{\rm HE} = 1.00, \eta_{\rm CHCP_e} = 0.36, \eta_{\rm CHCP_h} = 0.36, \eta_{\rm CHCP_c} = 0.34$
S1	#19	$\eta_{\rm T} = 0.97, \eta_{\rm HE} = 1.00, \eta_{\rm CHP_e} = 0.32, \eta_{\rm CHP_h} = 0.44$
S2	#19	$\eta_{\rm T} = 0.99, \eta_{\rm HE} = 0.95, \eta_{\rm CHP_e} = 0.26, \eta_{\rm CHP_h} = 0.40$
S 3	#19	$\eta_{\rm T} = 1.00, \eta_{\rm HE} = 1.00, \eta_{\rm CHP_e} = 0.30, \eta_{\rm CHP_h} = 0.40$
T1	#20	$\eta_{\rm T} = 1.00, \eta_{\rm GF} = 0.65, \eta_{\rm CHP_e} = 0.35, \eta_{\rm CHP_h} = 0.45$
T2	#20	$\eta_{\rm T} = 0.97, \eta_{\rm GF} = 0.75, \eta_{\rm CHP_e} = 0.30, \eta_{\rm CHP_h} = 0.42$
U1	#21	$\eta_{\rm T} = 1.00, \eta_{\rm GF} = 0.70, \eta_{\rm CHCP_e} = 0.30, \eta_{\rm CHCP_h} = 0.31, \eta_{\rm CHCP_c} = 0.30$
V1	#22	$\eta_{\rm T} = 0.97, \eta_{\rm CHCP_e} = 0.35, \eta_{\rm CHCP_h} = 0.37, \eta_{\rm CHCP_c} = 0.29, \eta_{\rm C_a} = 0.65, \eta_{\rm C_h} = 0.30$
W1	#23	$\eta_{\rm T} = 0.99, \eta_{\rm CHP_e} = 0.30, \eta_{\rm CHP_h} = 0.32, \eta_{\rm C_a} = 0.59, \eta_{\rm C_h} = 0.21$
W2	#23	$\eta_{\rm T} = 1.00, \eta_{\rm CHP_e} = 0.33, \eta_{\rm CHP_h} = 0.45, \eta_{C_a} = 0.50, \eta_{C_h} = 0.30$
X1	#24	$\eta_{\rm T} = 0.98, \eta_{\rm GF} = 0.76, \eta_{\rm CHCP_e} = 0.33, \eta_{\rm CHCP_h} = 0.40, \eta_{\rm CHCP_c} = 0.31, \eta_{\rm C_a} = 0.60, \eta_{\rm C_h} = 0.26$
Y1	#25	$\eta_{\rm T} = 1.00, \eta_{\rm GF} = 0.74, \eta_{\rm CHP_a} = 0.30, \eta_{\rm CHP_b} = 0.40, \eta_{\rm C_a} = 0.57, \eta_{\rm C_b} = 0.27$
Y2	#25	$\eta_{\rm T} = 0.98, \eta_{\rm GF} = 0.70, \eta_{\rm CHP_e} = 0.35, \eta_{\rm CHP_h} = 0.47, \eta_{\rm C_a} = 0.62, \eta_{\rm C_h} = 0.20$
Z1	#26	$\eta_{\rm T} = 1.00, \eta_{\rm HE} = 0.69, \eta_{\rm CHCP_e} = 0.30, \eta_{\rm CHCP_h} = 0.43, \eta_{\rm CHCP_c} = 0.26, \eta_{\rm C_a} = 0.63, \eta_{\rm C_h} = 0.23$
Γ1	#27	$\eta_{\rm T} = 1.00, \eta_{\rm HE} = 0.73, \eta_{\rm CHP_e} = 0.32, \eta_{\rm CHP_h} = 0.41, \eta_{\rm C_a} = 0.60, \eta_{\rm C_h} = 0.20$
Г2	#27	$\eta_{\rm T} = 0.96, \eta_{\rm HE} = 0.77, \eta_{\rm CHP_e} = 0.26, \eta_{\rm CHP_h} = 0.36, \eta_{\rm C_a} = 0.55, \eta_{\rm C_h} = 0.28$
Ψ1	#28	$\eta_{\rm T} = 0.96, \eta_{\rm HE} = 0.90, \eta_{\rm GF} = 0.70, \eta_{\rm CHCP_e} = 0.26, \eta_{\rm CHCP_b} = 0.32, \eta_{\rm CHCP_c} = 0.27, \eta_{\rm C_a} = 0.55, \eta_{\rm C_b} = 0.28$
Σ1	#29	$\eta_{\rm T} = 1.00, \eta_{\rm HE} = 0.95, \eta_{\rm GF} = 0.78, \eta_{\rm CHP_e} = 0.38, \eta_{\rm CHP_h} = 0.46, \eta_{\rm C_a} = 0.53, \eta_{\rm C_h} = 0.32$
Σ2	#29	$\eta_{\rm T} = 1.00, \eta_{\rm HE} = 0.95, \eta_{\rm GF} = 0.78, \eta_{\rm CHP_e} = 0.38, \eta_{\rm CHP_h} = 0.46, \eta_{\rm C_a} = 0.53, \eta_{\rm C_h} = 0.32$

		Cost Coeff	icients of Entire	e Energy			Energy Proc	luction Limits	
Hub Code	Hub Type	Cost Cooli	Telenas of Entire	, Energy			(pu)	_	Entire Energy
		<i>a</i> (mu)	b (mu/pu)	$c (mu/pu^2)$	d (rad/pu)	<i>e</i> (mu)	E _{min}	E _{max}	
Al	#1	80	200	25	100	4.2	0.10	0.75	Electricity
A2	#1	10	200	120	180	3.7	0.40	2.50	Electricity
BI	#2	20	150	65	-	-	0.50	3.40	Gas
Cl	#3	25	100	55	-	-	0.30	3.00	Gas
DI	#4	17	120	60	-	-	0.10	1.10	Gas
El	#5	10	250	100	-	-	0.20	0.50	Heat
F1	#6	30	180	60	140	4.0	0.20	1.25	Electricity
		20	170	90	-	-	0.10	1.00	Gas
F2	#6	12	210	100	160	3.8	0.30	1.75	Electricity
		25	100	40	-	-	0.10	1.40	Gas
G1	#7	18	190	110	130	4.1	0.10	1.00	Electricity
H1	#8	70	160	100	130	3.3	0.20	1.50	Electricity
		25	100	40	-	-	0.20	1.90	Gas
I1	#9	25	120	50	-	-	0.15	1.00	Gas
11	#10	20	150	60	-	-	0.10	1.10	Gas
51	#10	10	200	110	-	-	0.20	0.50	Heat
K1	#11	20	150	60	-	-	0.10	1.10	Gas
KI	#11	10	200	110	-	-	0.20	0.50	Heat
L1	#12	25	100	55	-	-	0.30	3.00	Gas
M1	#13	80	200	25	100	4.2	0.10	0.75	Electricity
IVI I	#13	15	150	200	-	-	0.10	0.90	Heat
N1	#14	80	200	25	100	4.2	0.10	0.75	Electricity
111	#14	25	100	40	-	-	0.20	1.90	Gas
01	#15	15	150	200	-	-	0.10	0.90	Heat
01	#15	20	170	90	-	-	0.10	1.00	Gas
P1	#16	10	220	60	-	-	0.10	3.20	Gas
Q1	#17	19	170	150	-	-	0.10	3.20	Gas
Q2	#17	12	200	70	-	-	0.20	2.70	Gas
		12	200	110	120	4.8	0.30	1.75	Electricity
R1	#18	25	110	70	-	-	0.10	1.40	Gas
		15	150	200	-	-	0.10	0.90	Heat
		10	220	160	190	3.6	0.20	1.10	Electricity
S1	#19	20	200	100	-	-	0.20	1.80	Gas
		12	170	210	-	-	0.10	0.70	Heat
		40	190	220	190	4.0	0.10	2.10	Electricity
S2	#19	34	235	185	-	-	0.10	1.00	Gas
		20	120	410	-	-	0.10	0.90	Heat
		80	280	420	220	3.3	0.10	1.80	Electricity
S3	#19	13	140	185	-	-	0.10	3.00	Gas
		40	220	110	-	-	0.10	1.50	Heat
T 1	1120	80	200	25	100	4.2	0.10	0.75	Electricity
11	#20	25	100	55	-	-	0.30	3.00	Gas
T 2	1120	90	170	230	70	3.9	0.10	1.75	Electricity
12	#20	20	90	65	-	-	0.30	3.00	Gas
T 1 1	#21	90	170	230	70	3.9	0.10	1.75	Electricity
01	#21	20	90	65	-	-	0.30	3.00	Gas
371	#22	40	240	180	130	3.6	0.20	1.20	Electricity
V1	#22	30	70	100	-	-	0.10	2.30	Gas
****		80	200	25	100	4.2	0.10	0.75	Electricity
WI	#23	25	100	40	-	-	0.20	1.90	Gas
		12	200	110	120	4.8	0.30	1.75	Electricity
W 2	#23	25	110	70	-	-	0.10	1.40	Gas
***		50	200	110	150	4.4	0.20	1.10	Electricity
XI	#24	35	190	120	-	-	0.20	1.80	Gas
		28	80	490	100	3.5	0.00	3.00	Electricity
Y1	#25	31	100	220	-	-	0.10	2.80	Gas
		33	175	360	90	44	0.00	2.70	Electricity
Y2	#25	39	170	160	-	-	0.00	2.00	Gas
		70	220	310	130	4.6	0.10	2.00	Electricity
71	#26	27	230	100	-		0.10	1.80	Gas
	#20	10	100	200			0.10	0.70	Heat
	I	10	100	200	-	1 -	0.10	0.70	ileat

Table A.2. Data of energy sources (units)

		95	130	300	90	4.9	0.20	1.90	Electricity
Γ1	Г1 #27	29	220	330	-	-	0.20	1.00	Gas
		32	135	110	-	-	0.10	0.50	Heat
		60	230	410	130	3.5	0.10	1.10	Electricity
Г2	#27	50	140	290	-	-	0.20	1.80	Gas
		20	215	220	-	-	0.20	1.70	Heat
		20	100	500	310	3.8	0.00	0.90	Electricity
Ψ1	#28	60	195	85	-	-	0.10	3.80	Gas
		48	265	380	-	-	0.20	1.40	Heat
		100	150	110	60	4.3	0.10	3.00	Electricity
Σ1	#29	20	230	90	-	-	0.10	1.00	Gas
		70	100	40	-	-	0.10	0.40	Heat
		30	200	160	160	3.2	0.20	1.60	Electricity
Σ2	#29	60	110	160	-	-	0.10	4.50	Gas
		30	210	40	-	-	0.10	0.80	Heat

628

Table A.3. Prohibited zones of electrical power sources (electrical generator units)

Hub Code	Hub Type	Prohibited Zones (pu)
A1	#1	[0.30, 0.35] [0.40, 0.50] [0.65, 0.70]
A2	#1	[0.80, 0.90] [1.50, 1.70] [2.00, 2.10]
G1	#7	[0.50, 0.60] [0.70, 0.80]
M1	#13	[0.30, 0.40] [0.60, 0.65]
V1	#22	[0.30, 0.35] [0.75, 0.80] [1.00, 1.05]
Y1	#25	[1.00, 1.10] [2.00, 2.10]
Σ1	#29	[0.40, 0.50] [1.00, 1.20] [2.50, 2.60]
Σ2	#29	[0.80, 0.90] [1.30, 1.35]

629

Table A.4. Total demands

Carrier	Demand (pu)
Electricity	12.0
Heat	9.5
Cool	0.7
Compressed Air	1.2

- 632 **Appendix B** Performance evaluation of SAL-TVAC-GSA on five benchmark functions 633 634 Five benchmark functions are selected to evaluate the SAL-TVAC-GSA performance. The results are 635 compared with GA, PSO, TVAC-GSA, and GSA techniques. Data of these functions is adopted from 636 [16]. Results of 50 independent runs are summarized in Table B.1. Accordingly, the obtained SAL-TVAC-637 GSA results in terms of mean and standard deviations, demonstrate that the proposed optimization 638 algorithm finds the better results (close to the global minimum) on benchmark functions than all other 639
- 640 presented algorithms.

641 Table B.1. Comparison of different algorithm mean and standard deviation for benchmark functions

Functions	GA [45]		PSO [45]		GSA [16]		TVAC-GSA [16]		SAL-TVAC-GSA	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
f_1	338.5516	361.4970	37.3582	32.1436	5.9908×10 ⁻⁴	1.2315×10 ⁻⁴	2.0145×10 ⁻⁶	9.9037×10 ⁻⁷	1.9627×10 ⁻⁶	1.0049×10 ⁻⁸
f_2	9749.9145	2594.9593	1.1979×10-3	2.1109×10 ⁻³	1.9094×10-5	5.2031×10 ⁻⁵	4.1744×10-7	1.6791×10 ⁻⁸	4.1123×10 ⁻⁷	1.5539×10 ⁻⁸
f_3	3.6970	1.9517	0.1460	0.4182	≪10-300	≪10-300	≪10-300	≪10-300	≪10-300	≪10-300
f_4	-1.0298	3.1314×10-3	-1.0160	1.2786×10 ⁻²	-1.0316283219	6.7103×10 ⁻⁶	-1.0316283597	6.7752×10 ⁻⁹	-1.03162845348	3.1012×10-9
f_5	7.9610	1.5063	0.4123	0.2500	1.6627×10 ⁻¹⁷	2.3145×10 ⁻¹⁶	3.3201×10 ⁻²⁷	1.7611×10 ⁻²⁹	1.5700×10 ⁻²⁸	8.1295×10 ⁻³¹

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