Reliability centered economic dispatch in concept of energy hub considering resource diversity constraint

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In an inconsistent view of energy systems, the interaction between different energy carriers is not taken into account. In such a view, the considered problem is not well optimized. The idea of an integrated looking into several carriers has been proposed by creating the energy hub concept. Due to the simultaneous attention of all energy carriers, long-term planning and short-term operation have converted to complicated challenges. To this end, this study focuses on the energy hub operation for cost minimization. In addition to considering reliability indices for different loads, diversity constraint is regarded as a key point to increase energy security. Sensitivity analysis of the degree of diversity and its effects on operation costs and Expected Energy not Supply (EENS), play a vital role in the final decision. LINDOGlobal solver is employed in GAMS to implement Mixed Integer Nonlinear Programming (MINLP) model. A sample energy hub, considering three carriers in the input port and three loads in the output port, is used as a test system, and results are discussed in depth.

keywords: *Energy hub, Economic Dispatch, Diversity Constraint, Reliability.*

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NOMENCLATURE

$i\,(\alpha,\,\beta,...,\gamma)$	Index for hub's input energy carrier
$j\,(\alpha',\,\beta',...,\gamma')$	Index for hub's output energy carrier
m	Index for converter type
n	Index for number of installed component
t	Index for time block
s	Index for energy storage
N_i	Number of hub's input energy carrier
N_o	Number of hub's output load
N_m	Number of energy converters
N_n	Number of installed component
N_s	Number of energy storage
N_t	Number of time blocks
P_i	i^{th} input energy
L_j	j^{th} output load
P	Input matrix
L	Output matrix
C	Coupling matrix
L_{Co}	Converter matrix
L_{St}	Storage matrix
η_{Trans}	Transformer efficiency
η^{e}_{CHP}	CHP electrical efficiency
η_{Fr}	Furnace efficiency
η_{Exe}	Heat exchanger efficiency
η_{E}	Electrical efficiency
η_{Th}	Thermal efficiency
η_{C}	Cooling efficiency
TC	Total energy hub cost
$\pi - EC$	Price of energy carrier
$VOLL$	Value of los load
Pin_Tot	Total input of energy hub
$Pout\_Tot$	Total input of energy hub
Pin	Input energy
$Pout$	Output energy
Sin	Input power of storage
$Sout$	Output power of storage
θ^{dis}	Discharging rate of storage
θ^{ch}	Charging rate of storage
SE	Stored energy in storage

η	Component efficiency
Pin^{min}	Minimum input power of converter
Pin^{max}	Maximum input power of converter
Sin^{min}	Minimum input power of storage
Sin^{max}	Maximum input power of storage
Sou^{min}	Minimum output power of storage
$Sout^{max}$	Maximum output power of storage
SE^{min}	Minimum stored energy in storage
SE^{max}	Maximum stored energy in storage
I	Installation significance (1=installed, 0=else)
DF	Diversity Factor
Pin_{Norm}	Normalized input energy
x	Amount of each inputs
$\hat{x}$	Normalized x
$Ln(\hat{x})$	$Log_e^{\hat{x}}$

1. INTRODUCTION

Classically, cost minimization has always been a main concern of researchers in various studies on different energy systems. One of the main objectives of control centers is secure and reliable operation of energy systems. So besides the system total cost minimization, it is important to achieve acceptable and specific levels of adequacy and security within energy system. There is an important trade-off between total system cost minimization and achieving an appropriate level of reliability in energy systems.

On the other hand, developing infrastructures of energy carriers and increasing different types of demands have led a significant view at energy carriers. In fact, the concept of energy hub has emerged as a common thread of different carriers from the aforesaid idea. Traditionally, various studies of different energy systems used to be conducted separately and independently. Contrarily, the interaction of different energy carriers on a centralized scale has been developed by energy hub [1].

In recent years, many literatures have been conducted on the concept of energy hub. Geidle and colleagues have proposed energy hub as a powerful approach for framework in energy systems and presented basic integrated modeling of multi carriers [2, 3]. Long-term integrated planning in interconnected energy system that considers interdependency of electricity and gas infrastructures has been presented in [4, 5]. Authors in [6] have presented the probabilistic model for solving demand response problem in integrated energy hub based on MINLP. Moreover, robust optimization for solving smart micro energy hub (SMEH) considering hydrogen storage system and demand response proposed in [7]. Also, optimization of power and natural gas networks considering several uncertainties based on information gap decision theory and scenario based approach has been presented in [8]. References [9–12]have focused on uncertainty in management, operation and design of energy hub affected by renewable energy such as wind and photovoltaic. Krapels has explained the program of energy in New-York uses an energy hub concept [13]. A multi-objective partial swarm optimization based method has been modeled in [14] for managing hybrid electric vehicles charging patterns in the context of energy hub. Optimal structure design and sizing of energy hub components in the long term has been investigated in [15]. Optimum load management in residential and industrial energy hub has been presented in [16, 17] respectively. Mirzaei and colleagues have presented risk-constrained energy hub system integrated with compressed air energy storages and power-to-gas [18]. Also, transient model of solar heating, ventilation and cooling system in real house is developed in [19]. Authors in [20, 21] have applied game theoretic for deploying management and scheduling in smart energy hub. Reference [22] has presented the real design model of heat exchanger as one of the important component in power plant considering fatigue and life time analysis. Perfect modeling of evaporating desalination system including all sub-systems has been introduced in [23]. Authors in [24] have introduced integrated cogeneration structure consisting of power plant, solar and desalination systems.

In Recent years, a review of various energy hub issues has come to the attention of researchers. Mohammadi and colleagues have a presented comprehensive review about multi-energy systems and energy hub [25]. Also, review study with focus on energy positive neighborhoods has been published in [26]. Also, review of energy hubs scheduling in presence of uncertainty is presented in [27]. Authors in [28] have reviewed the management of smart energy hubs.

Furthermore, considering reliability evaluations in energy hub studies is essential. For this purpose, uncertainty should be taken into account for the performance of elements. In fact, certain questions should be answered: What is the load supplying situation when a fault occurs in equipment? What are the values of reliability indices [29, 30].

Since different energy carriers are employed in input port of an energy hub, it is efficient choice and appropriate to use all of them without insisting on applying only one carrier. This phenomenon potentially increases energy security. In other words, imposing a diversity constraint means not insisting on providing different loads by using a specific carrier [31].

In [32, 33], energy security has been studied thoroughly. Moreover, key definitions were provided for certain concepts such as energy security, climate change and ambiguity of energy security in addition to the dimensions of sustainable, political, environmental and social developments. It should be noted that mentioned researches are usually regarded as the main reference in studies on energy security.

In [34, 35], a comprehensive review has been conducted to analyze energy security in the recent decade. In fact, energy security has been defined differently in various references. Availability (elimination of dependency on one technology), infrastructure (the number of production units and lines), price (fixed and competitive), social impacts (increased population and consumption), environmental impacts (pollution), governmental-political impacts (subsidies and international relations) and productivity are basic concepts.

This study presents security constrained operation of energy hub. For this purpose, the economic dispatch is regarded as the primary problem in which reliability calculations and diversity constraint are evaluated simultaneously. Where, a penalty factor for the failure to provide different loads are added to classical objective function. So that the Expected Energy not Supply (EENS) reaches acceptable levels. For the sake of clarity, different values of diversity are considered in sensitivity analysis about total cost and reliability indices.

The rest of paper is organized as follows: In section 2, the basic concepts of energy hub, the reliability centered economic dispatch problem of energy hub and diversity significance are explained. Eventually, test system, assumptions and results are described and analyzed in section 3.

2. METHODOLOGY

A. Energy Hub Modeling

From a structural point of view, energy carriers enter the input port of an energy hub and are divided into converters. Meanwhile, different loads are supplied through the output port and certain amounts of energy may charge storage devices. It is notable that the concept of energy hub is not limited to a specific size of modeled systems. Indeed, this approach enables researchers to simulate a large number of energy carriers and products in input/output ports. Therefore, it provides more flexibility to model systems than conventional ones. Some of mentioned systems are as follows [2, 36]:

- Power plants
- Industrial facilities and factories
- Large buildings such as universities, airports, hospitals and hotels
- Geographical regions such as cities and villages

Systematically, connecting and combining different energy carriers in energy hub and adding diversity to inputs and sources will bring about effective advantages over the conventional and separated demand supply methods. For instance, some of them are as follows: higher energy security, flexibility in the supply loads and synergy effects.
In fact, an energy hub can be regarded as a Multi-Input/Multi-Output (MIMO) system illustrated in Fig. 1 and it can be formulated mathematically as follows [2, 37]:

$$\begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\gamma \end{bmatrix}_{m\times 1} = \begin{bmatrix} c_{\alpha\alpha'} & c_{\alpha\beta'} & \cdots & c_{on'} \\ c_{\beta\alpha'} & c_{\beta\beta'} & \cdots & c_{\beta n'} \\ \vdots & \vdots & \cdots & \vdots \\ c_{\gamma\gamma'} & c_{\gamma'} & \cdots & c_{\gamma'} \end{bmatrix}_{m\times n} \begin{bmatrix} P_{\alpha'} \\ P_{\beta'} \\ \vdots \\ P_{\gamma'} \end{bmatrix}_{n\times 1}$$
$$\Rightarrow L_{m\times 1} = C_{m\times n} \times P_{n\times 1} \qquad \textbf{(1)}$$

Coupling matrix array (C_{ij}) shows the relation between the j^{th} output load and j^{th} input energy. As it can be inferred, generally the coupling matrix is rectangular by nature ($m \times n$). Additionally, each carrier in the input of hub can be shared into several converters. For example, in Fig. 2 specified energy carrier divided into k parts (the k^{th} convertor is supplied by $v_{i,k} \times P_i$ as a part of the i^{th} energy carrier).
Therefore, constraints (2) and (3) can be written [9]:

$$P_{i,k} = v_{i,k} \times P_i \forall i,k \qquad \textbf{(2)}$$

$$\sum_k v_{i,k} = 1 \quad \forall i \qquad \textbf{(3)}$$
$$0 \le v_{i,k} \le 1$$

For the sake of clarity, the equations of sample energy hub presented in Fig. 3 can be described step-by-step as follows:

$$\begin{bmatrix} P_e \\ P_{g1} \\ P_{g2} \\ P_h \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & v & 0 \\ 0 & 1-v & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} P_e \\ P_g \\ P_h \end{bmatrix} \qquad \textbf{(4)}$$

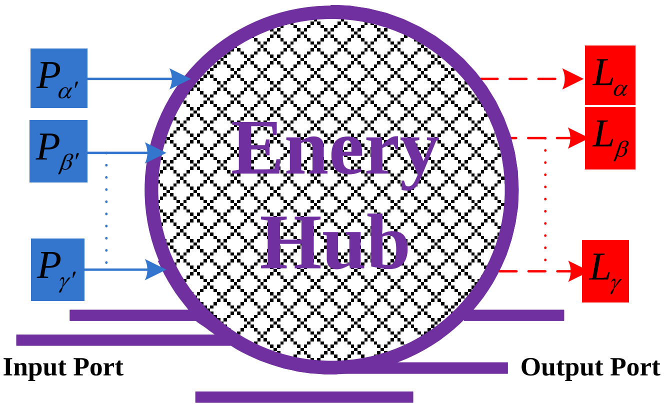

Fig. 1. Conceptual form of energy hub as a multi-input/multi-output system

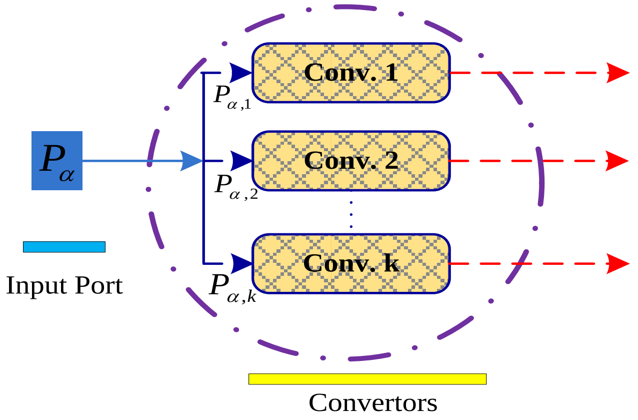

Fig. 2. The division of certain carrier into different convertors

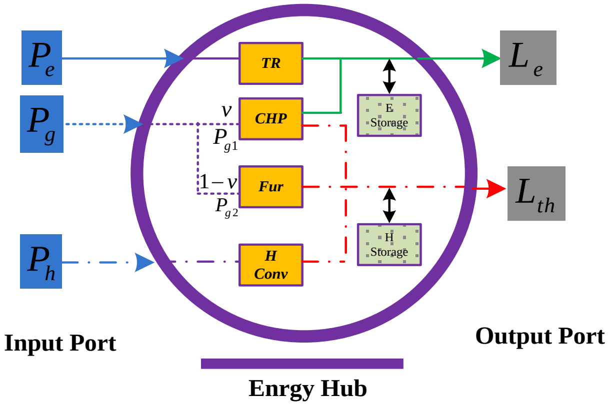

Fig. 3. Sample energy Hub considering tree inputs and two outputs

$$\begin{bmatrix} L_e \\ L_{th} \end{bmatrix} = L_{\mathrm{Co}} + L_{St}$$

$$A = \begin{bmatrix} \eta_{\mathrm{Trans}} & \eta^{e}_{CHP} & 0 & 0 \\ 0 & \eta^{th}_{CHP} & \eta_{Fr} & \eta_{Exe} \end{bmatrix} \begin{bmatrix} P_e \\ P_{g1} \\ P_{g2} \\ P_h \end{bmatrix} \tag{5}$$

$$B = \begin{bmatrix} \mathrm{Sout}_e - \mathrm{sin}_e \\ \mathrm{Sout}_h - \mathrm{sin}_h \end{bmatrix}$$

B. Reliability Centered Economic Dispatch of the Energy Hub

The main objective function in reliability centered economic dispatch is defined by minimizing total operation costs, in which the prices of different energy carriers and the penalty factor for the violation of EENS play key roles [38]. This function can be stated in (6) [15, 39]:

$$\left(\sum_{i=1}^{N_i}\sum_{t=1}^{N_t} \pi\_EC_{i,t} \times Pin - Tot_{i,t}\right) + \left(\sum_{j=1}^{N_j}\sum_{t=1}^{N_t} VOLL_j \times EENS_{j,t}\right) \tag{6}$$

As well, the technical constraints on system and components are as follows:

- Input port balance:

$$\mathrm{Pin\_\ Tot}_{i,t} = \sum_{m=1}^{N_{\mathrm{m}}}\sum_{n=1}^{N_n} \mathrm{Pin}_{i,m,n,t} \tag{7}$$

- Output port balance:

$$\left(\sum_{m=1}^{N_m}\sum_{n=1}^{N_n} Pout_{j,m,n,t}\right) + \left(\sum_{s=1}^{N_s}\sum_{n=1}^{N_n} \left(\mathrm{Sout}_{j,s,n,t} - \mathrm{Sin}_{j,n,t}\right)\right) \tag{8}$$

- Charge and discharge of storages:

$$SE_{s,nt} = SE_{s,n,t-1} - \left(\frac{Sout_{s,n,t}}{\theta^{dis}_{s}}\right) + \left(\mathrm{sin}_{s,n,t} \times \theta^{ch}_{s}\right) \tag{9}$$

- Input/Output energy of converters:

$$\mathrm{Pout}\ _{j,m,n,t} = \sum_{i=1}^{N_i} \left(\eta_{i,j,m} \times Pin_{i,m,n,t}\right) \tag{10}$$

- Converters limits:

$$I_{m,n} \times Pin^{\mathrm{min}}_{i,m} \le \mathrm{Pin}_{i,m,n,t} \le I_{m,n} \times Pin^{\mathrm{max}}_{i,m} \tag{11}$$

- Storages limits:

$$\begin{gathered} I_{s,n} \times \mathrm{sin}^{\mathrm{min}}_{s,n,t} \le \mathrm{sin}_{s,n,t} \le I_{s,n} \times \mathrm{sin}^{\mathrm{max}}_{s,n,t} \\ I_{s,n} \times Sout^{\mathrm{min}}_{s,n,t} < Sout_{s,n,t} \le I_{s,n} \times \mathrm{Sout}^{\mathrm{max}}_{s,n,t} \\ I_{s,n} \times SE^{\mathrm{min}}_{s} \le SE_{s,n,t} \le I_{s,n} \times SE^{\mathrm{max}}_{s} \end{gathered} \tag{12}$$

Also, regarding the integrity of reliability, EENS as well-known index is calculated for all of the consumption loads according to (13)-(16) [15, 39]:

$$\begin{aligned} EENS_j &= \sum_{t=1}^{N_t} EENS_{j,t} \\ EENS_{j,t} &= \sum_{el=1}^{N_{el}}\sum_{n=1}^{N_n} \left(pr_{j,el,n,t} \times ENS_{j,el,n,t}\right) \end{aligned} \tag{13}$$

$$pr_{j,el,n,t} = \left(I_{el,n} \times FOR_{el,n}\right) \times \prod_{el=1}^{N_{el}}\prod_{n=1}^{N_n} \left(1 - \left(I_{el,n} \times FOR_{el,n}\right)\right) \tag{14}$$

$$ENS_{j,el,n,t} = Ltot_{j,t} - \sum_{el=1}^{N_{el}} \sum_{\begin{cases} \hat{n} = 1 \\ n \neq n \end{cases}}^{N_n} \left(\mathrm{Res}_{j,el,n,t} + PSout_{j,d,nt}\right) \tag{15}$$

$$\mathrm{Re}\, s_{j,el,n,t} + PSout_{j,el,n,t} \le I_{el,n} \times PSout^{\mathrm{max}}_{j,el,n} \tag{16}$$

In addition, equation (17) shows the normalized diversity illustrated in section C:

$$\begin{gathered} -\frac{\sum\limits_{i=1}^{N_i} \left(\mathrm{Pin\_Norm}_i \times \ln Pin\_\mathrm{Norm}_i\right)}{\mathrm{Ln}(N_i)} \ge DF \\ \mathrm{Pin\_Norm}_i = \frac{\left(\sum\limits_{t}^{N_t} \mathrm{Pin\_}\,Tot_{i,t}\right)}{\sum\limits_{i}^{N_i}\sum\limits_{t}^{N_t} \mathrm{Pin{-}Tot}_{i,t}} \end{gathered} \tag{17}$$

C. Diversity Constraint and Evaluation

Variety or diversity is an extensive and interesting topic in economy of energy. The concept of diversity was introduced in engineering during the 1970s, especially in sectors dealing with natural resources. As a matter of fact, in an energy system with several inputs, appropriate proportions of carriers should be employed to supply the required loads. Based on this capability, diversity constrains efforts to achieve an acceptable level of energy security, including: availability, reliability, affordability and sustainability. In such strategy, there should not be any emphasis on the use of a particular carrier. Generally, energy diversity is achieved through the balanced reliance on different available options in the input. In [32, 34], the diversity index (Shanon-Wienner) has been introduced based on the amount of each input (x_i) as follows:

$$\begin{aligned} &\mathrm{Diversity} = -\sum_{i=1}^{N_i} \left(\hat{x}_i \times \mathrm{Ln}\left(\hat{x}_i\right)\right) \\ &\hat{x}_i = \frac{x_i}{\sum\limits_{i=1}^{N_i} x_i} \\ &\mathrm{Diversity}_{\mathrm{max}} = \mathrm{Ln}\left(N_i\right) \\ &\Rightarrow \mathrm{Diversity}_{\mathrm{Norm}} = \frac{-\sum\limits_{\mathrm{i}=1}^{\mathrm{N_i}} \left(\hat{\mathrm{x}}_{\mathrm{i}} \times \mathrm{Ln}(\hat{\mathrm{x}}_{\mathrm{i}})\right)}{\mathrm{Ln}(\mathrm{N_i})} \end{aligned} \tag{18}$$

For simplification, the diversity factor calculations for sample system with five inputs (N=5) are illustrated in Tabel 1:
Since the maximum diversity constraint is equal to Ln(N), the normalized diversity will be equal or less than one.

Table 1. Sample calculations of diversity factor

$\hat{x}_i$	$\frac{x_i}{\sum_{i=1}^{N_i} x_i}$	$Ln(\hat{x}_i)$	$\hat{x}_i \times Ln(\hat{x}_i)$	$-\sum_{i=1}^{N_i}(\hat{x}_i \times Ln(\hat{x}_i))$
60	0.60	-0.51	-.0.31	1.07
25	0.25	-1.39	-0.35	
10	0.01	-2.30	-0.23	
4	0.04	-3.22	-0.13	
1	0.01	-461	-0.05	
$Diversity_{max} = Ln(N_i) = Ln(5) = 1.61$ $Diversity_{Norm} = \frac{1.07}{1.61} = 0.66$				

In this paper, sensitivity analysis is performed by values of diversity in different operating conditions. Then, the effect of these values on other parameters will be investigated.

3. RESULTS AND DISCUSSION

A. Case Study and Assumptions

Energy system consists of different carriers as input port and three types of loads as output port illustrated in Fig. 4 used as a test system. As it can be seen, electricity, gas and heat supply electrical, thermal and cooling demands. Furthermore, amount of loads in time horizon and related prices are presented in Fig. 5 and Fig. 6 respectively [40]. Also, Table 2 indicates the technical specifications of energy hub components.

It is notable that the maximum number of installed components is assumed to be equal to seven for each of them. Energy (power), cost, and energy prices are assumed per unit (p.u.) with the base quantities as follows: 1 kW, 0.01 $, and 0.01 $ per 1 kW. Furthermore, value of loss load is assume to be 210, 320 and 550 $/kw for cooling, thermal and electrical loads respectively. For the sake of research integrity, different scenarios shown in Table 3 are also considered. Also, the equations and notes related to each scenario are shown in Table 4.

Moreover, LINDOGlobal [41, 42] was used to solve the aforementioned problem in GAMS and main assumptions are as follows: 1) Feasibility tolerance for nonlinear constraints is set to 10^{-6}, 2) Default number of iterations is set to 2×10^{-9}, 3) Running time is set 2000 sec and 4) Tolerance for the gradients of nonlinear functions is set to 10^{-6}. Also, computer with 5 GHz CPU and 16 GB RAM is used to perform the simulation.

B. Results

At the outset, Fig. 7 shows the total cost (operation and penalty) without considering the diversity constraint. As already mentioned, in the first and second scenarios (Sc1 and Sc2), reliability evaluation (EENS) is not taken into account as constraints and the mentioned index is calculated after the optimization procedure. It is reasonable to say that in the third and fourth scenarios (Sc3 and Sc4) where the reliability evaluations are considered as constrains, the values of the relevant index are more appropriate. Related EENS and the basic values of diversity are reported in Table 5. Furthermore, Fig. 7 and Fig. 8 show the penalty and operation costs.

It's worthy to mention that, if the diversity value is set to a certain rate or less than its specified target, which is obtained in the base state, incurs the solution to be infeasible in optimization

Table 2. Technical details of energy hub elements

Hub Element	Max InputPower	Min Input Power	η_E	η_{Th}	η_C	FOR
TR	12	0.12	0.98	-	-	1.50
CCHP	20	0.21	0.35	0.25	0.21	3
Fur	10	0.10	-	0.81	-	2
HE	1	0.10	-	0.72	-	3
EStorage	5	0	0.95	-	-	3
HStorage	3	0	-	0.91	-	3
CStorage	3	0	-	-	0.93	3
All storages: MaxEnergy=10 All storages: MinEnergy=0.50						

Table 3. Different scenarios for analyzing energy hub operation

	Reliability	Energy storage
Scenario1 (Sc1)	×	×
Scenario2 (Sc2)	×	√
Scenario3 (Sc3)	√	×
Scenario4 (Sc4)	√	√

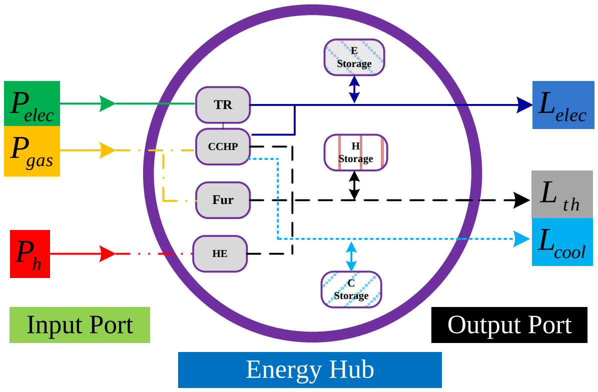

Fig. 4. Structure of sample Energy hub as test system

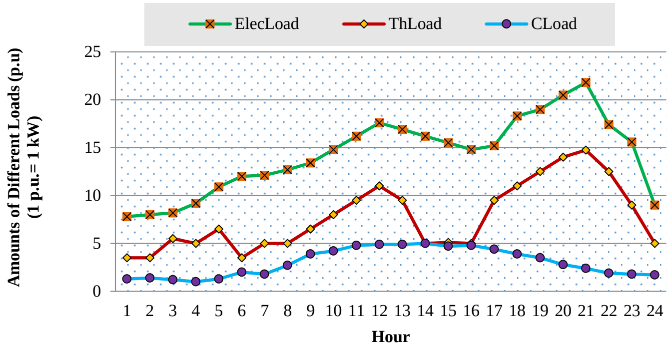

Fig. 5. Different loads in output port of energy hub

Table 4. Equation and notes related to each scenario

	Sc1	Sc2	Sc3	Sc4
Objective Function	(6) without Penalty Cost	(6) without Penalty Cost	(6)	(6)
Constraints	(9)-(14)	(9)-(14)	(9)-(19)	(9)-(19)
Notes	$I_{s,n} = 0$		$I_{s,n} = 0$	
	EENS and relate cost are calculated after the optimization procedure		EENS and related cost are calculated in the optimization procedure	

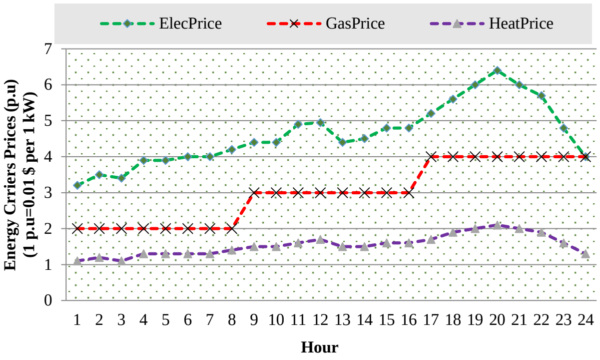

Fig. 6. Different energy carriers' prices in input port

process. Also, due to the constraints of the problem, the amount of diversity can't be greater than certain margin. Subsequently, the diversity constrain should be governed by greater than or equal to the corresponding values in the Table 5.

In addition, depending on the values given to the diversity, Table 6 shows the total cost. It is reasonable to say that creating diversity manipulates the arrangement of energy carriers in input port and make them lose optimal economic condition. For instance, inputs of the second scenario are shown in the Fig. 9 (the initial state) and Fig. 10 (the maximum amount of diversity) and operation cost changes for first scenario is shown in Fig. 11. However, in point of energy security view, making diversity is essential and necessary.

Also, Table 7 and Fig. 12 illustrate EENS and relate costs for different loads according to the maximum value of diversity factor. It is recognized that with rising diversity, the proposed indices may change, which, due to the amount of diversity, cause a decreasing or incremental effect. The more the carrier share of the specified load supplier increases, the more the associated reliability level rises, and vice versa. Having been somehow included in the Sc3 and Sc4 by reliability constraints, EENS is not highly affected by changing the diversity value.

As it can be seen, according to results, the operation cost of the first scenario is higher than other scenarios, a fact that shows the most noneconomic operation conditions. On the other hand, the fourth scenario is properly selected as the best case and most operational one, because of benefiting from reliability and storage components.

Table 5. EENS and diversity factor for different scenario in base case

	E-Load	Th-Load	C-Load	$Diversity_{norm}$
Sc1	2.4465	1.2058	2.0987	0.967
Sc2	0.136	0.765	1.1339	0.9753
Sc3	0.0151	0.0839	0.0801	0.923
Sc4	≈ 0	0.0005	≈ 0	0.9682

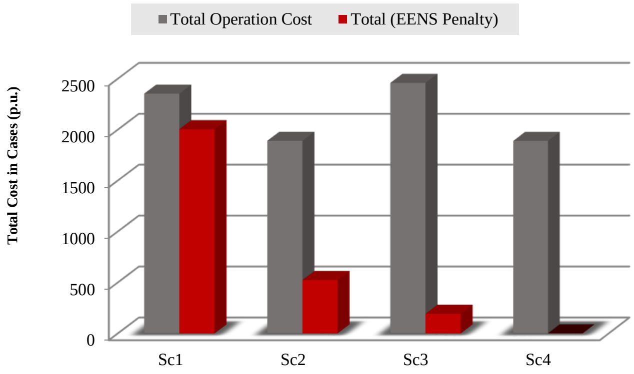

Fig. 7. Total operation and penalty costs in each scenario

Selecting the proper diversity for the appropriate energy hub operation is an important and fundamental problem, which is even associated with political, national topics and grid codes. To this end, the operator is responsible for making the correct decision about the determination of diversity value. What matters is that developing diversity plays a vital role in the concepts of energy security and in such application it takes precedence over financial issues. Meanwhile, regarding to the diversity concept, there is not any specified prescription working for all systems and systems should be evaluated case by case.

4. CONCLUSIONS

This study concerned the economic dispatch problem in the concept of energy hub which total cost is considered as objective function. Beside this, reliability assessment was developed for

Table 6. Comparing the operation cost according to the diversity

	Operation Cost in Base Case Diversity	Operation Cost in Maximum Diversity
Sc1	2297.4282	2315.6375
Sc2	2014.2591	2169.1367
Sc3	2296.719	2298.1032
Sc4	2015.3128	2015.3401

Table 7. EENS for maximum value of diversity factor

	E-Load	Th-Load	C-Load	$Diversity_{max}$
Sc1	1.285	0.0829	0.2838	0.9697
Sc2	0.2351	0.0326	1.126	0.9925
Sc3	0.0153	0.0841	0.0803	0.9697
Sc4	≈ 0	0.0005	≈ 0	0.9776

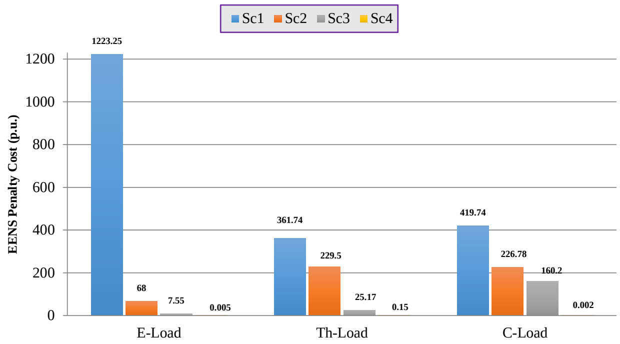

Fig. 8. Penalty cost in each scenario for base case

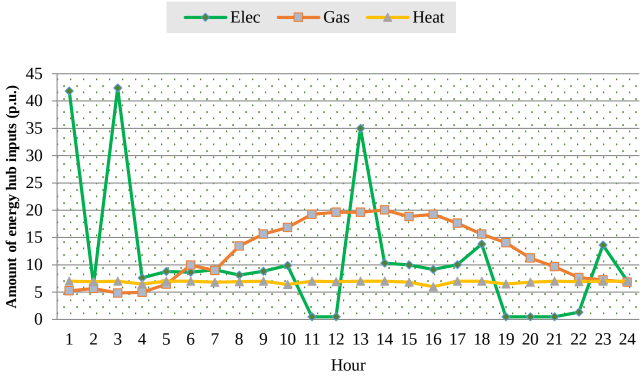

Fig. 9. Amount of energy hub inputs in Sc2 (base case)

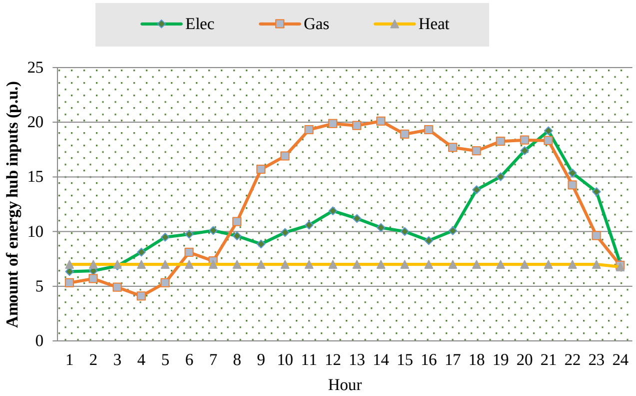

Fig. 10. Amount of energy hub inputs in Sc2 ($Diversity_{max} = 0.9925$)

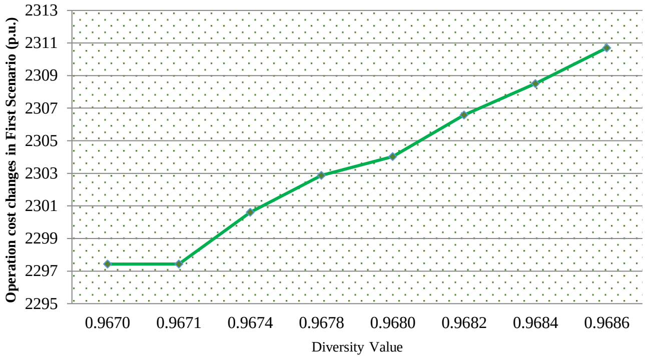

Fig. 11. Analysis of Operation cost in Sc1

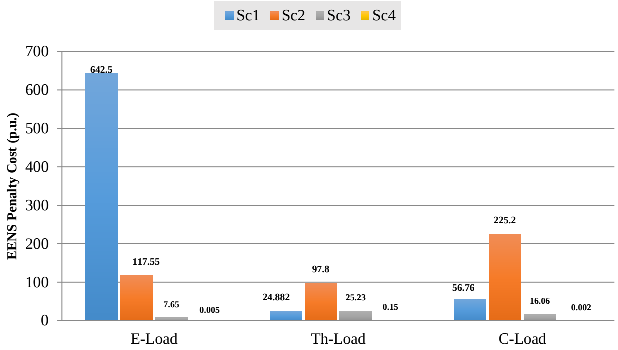

Fig. 12. Penalty cost in each scenario for maximum value of diversity

different loads in the output port. Moreover, the diversity is introduced as a key and auxiliary constraint on the energy hub operation to diversify the use of input carriers and the balanced reliance on them. An analysis was also conducted on the interaction between costs, indices of reliability and diversity value. Based on simulation results, it is argued that diversification of inputs usually increased the operation cost because of considering constrain to detection of each input through optimization. Based on the results obtained in different scenarios, it can be concluded that with an increase of 1% in the value of diversity, total cost nearly increases by 2.8%, 4.36%, 0.012% and 0.001% in scenarios1-4 respectively. It should also be noted that diversification is often interpreted along the concept of increased energy security in energy topics.

The management of interconnected hubs in long-term planning and the use of multi-objective optimization are considered as our future research field.

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