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Multi Energy System With an Associated Energy Hub: A Review

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ABSTRACT The increasing penetration of renewable resources causes some challenges like the electric power demand prediction uncertainty and energy surplus. Energy storage systems (ESS) are promising solutions for these challenges. However, considering the marginal capacity of ESSs according to the installation area and the economic portion of ESSs according to the installation capacity, the use of battery ESSs to reduce surplus energy is not efficient and has practical limitations. To efficiently resolve the challenges, a multi-energy system (MES) that is capable of operating different energy sources, such as natural gas storage (NGS), thermal energy storage (TES), ice energy storage (IES), and hydrogen energy storage (HES) has been proposed. The centerpiece of converting and managing multiple energy sources associated with the MES is the energy hub (EH). In this paper, we reviewed and compared the performance of existing ESSs and the MES, and the results have demonstrated the superiority of the MES. In addition, EHs that include power-to-gas, combined heat power, and combined cooling heat power, have been examined based on their structural characteristics. A review of the methods and the primary purpose of MES is also highlighted in this paper.

INDEX TERMS Combined cooling heat power (CCHP), combined heat power (CHP), power to gas (P2G), microgrid, reliability, multi-energy system (MES), energy hub (EH).

NOMENCLARUE

MES	Multi Energy System.
EH	Energy Hub.
CHP	Combined Heat & Power.
CCHP	Combined Cooling Heat & Power.
P2G	Power to Gas.
ESS	Energy Storage System.
BES	Battery Energy Storage.
TES	Thermal Energy Storage.
IES	Ice Energy Storage.
NGS	Natural Gas Storage.
Elz	Electrolyzer.
FC	Fuel cell.
GT	Gas Turbine.
GB	Gas Boiler.
Ach	Absorption chiller.
HRS	Heat Recovery System.
EC	Electric Chiller.
WH	Wood Heat.
TR	Transformer.
SOFC	Solid Oxide Fuel Cell.
MCFC	Molten Carbonate Fuel Cell.
SOC	State Of Charge.
NG	Natural Gas.
MILP	Mixed Integer Linear Programming.
MIP	Mixed Integer Programming.
LP	Linear Programming.
NLP	Nonlinear Programming.
MPOD	Multi-Period Optimal Dispatch.
MISCOCP	Mixed Integer Second-Order Cone Programming.

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BONMIN	Basic Open-source Nonlinear Mixed-Integer Programming.
FOA	Fruit fly Algorithm.
CGA	Compact Genetic Algorithm.
HS	Human Strategy.
GA	Genetic Algorithm.
EVPI	Expected Value of perfect Information.
RO	Robust Optimization.
VSS	Value of the Stochastic Solution.
SO	Stochastic Optimization.
PSO	Particle Swarm Optimization.
TLBO	Teaching Learning-Based Optimization.
TACMA	Total Annual Cost Minimization Algorithm.
ADMM	Alternating Direction Method of Multipliers.
FOR	Forced Outage rated.
LOLP	Loss of Load Probability.
MAIFI	Momentary Average Interruption Frequency Index.
CAIFI	Customer Average Interruption Frequency Index.
CAIDI	Customer Average Interruption Duration Index.
SAIDI	System Average Interruption Duration Index.
SAIFI	System Average Interruption Frequency Index.
LOGP	Loss of Gas-load Probability.
LOLE	Loss of Load Expectation.
LOEE	Loss of Energy Expectation.
EENS	Expected Energy Not Supplied.
EGNS	Expected Gas Not Supplied.
ASAI	Average Service Availability Index.
ECOST	Expected customer interruption COST.
IPM	Interior Point Method.

I. INTRODUCTION

Due to the rapid increase in energy generation from renewable sources, flexibly using multiple energy sources as an efficient avenue for surplus power utilization attracts significant attention. Renewable energy sources, such as the wind and solar energy, usually generate an intermittent power surplus. These sources are characterized by a power prediction based on the probability distribution because of their unstable output [1]–[3]. In contrast to the steadily increasing surplus power associated with renewable energy sources, the capacity of battery energy storage system (BESS) systems, which store electric energy, is limited [4]. A multi-energy system MES can ensure the energy supply reliability and efficiency by continuously supplying energy from different sources. The MES is capable of providing energy through the efficient use of wasted energy, even if there is a problem with the energy supply. To configurate a MES, the energy conversion between multiple sources is a primary consideration. Such energy conversion is adequately explained using the energy hub (EH) concept. The EH is an energy conversion and management system where the input energy variables $(x_1, x_2, \ldots, x_n)$ are represented as the output energy variables $(y_1, y_2, \ldots, y_n)$ for different energy types [5]. Many projects and previous studies have built EH in MES through sector coupling based on renewable energy sources. In this study, the concept of EH is evaluated using three well-known technologies, followed by an integrated MES construction.

The first technology is the power to gas (P2G) technology, in which surplus power is generated by converting renewable energy to gas energy through hydrogenation and methanation, which can then be supplied, stored, or consumed [6]–[8]. The main components of the P2G system are the electrolyzer (Elz) for generating hydrogen through the electrolysis of water and the hydrogen energy storage system (HESS) for storing the generated hydrogen [9]. Reversely, in the gas to power (G2P) technology, electric energy is generated using hydrogen energy as the input through the operation of fuel cells (FCs). However, in the present study, both the P2G and G2P are considered as P2G technology. In [10], the state of charge (SOC) of the HESS was analyzed, and a method for efficiently operating the system was proposed. In [11], the FC using hydrogen energy was researched, motions were predicted, and cells were designed as molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) in consideration of cell temperature, anode off-gas recirculation, reactant temperatures and fuel and oxidant utilization factors. The optimal capacity of the P2G components was calculated in [12] according to the renewable energy penetration associated with the exchange of gas and electric energy from the P2G components and a gas-fired generator. Meanwhile, in [13], the optimal capacity was calculated through the economic optimization of natural gas storage (NGS) system, in which natural gas (NG) generated through the P2G is stored based on the renewable energy shares. An economic analysis of the P2G technology based in Germany was performed in [14]. In [15], energy was converted and supplied from a natural gas grid to the power system by introducing an NGS incorporating the forced outage rate (FOR) into the natural gas grid, and the reliability of the gas and power systems was verified. Further, an economical operation method for the P2G technology was derived in [16] by curtailing loads of photovoltaic (PV) and wind generators.

The second technology considered is the combined heat and power (CHP) technology. The basic structure of a CHP system consists of the integration of heat and electricity systems. An EH structure for MES was modeled in [17] using the CHP system. The representative components of the CHP structure include a gas turbine (GT) and a heat recovery system (HRS) [18]–[20]. In this system, NG is employed as the input energy, and electricity is generated through the GT, while the heat produced as waste is supplied as heat energy through the HRS [21]–[29]. An optimal combination of the electric heat pump (EHP) and CHP systems has been investigated by [30], [31]. In [32], the economics of using a micro CHP system with an electric boiler (EB) at home was studied, while in [33], a method for improving the efficiency of the CHP system using the Kalina cycle process was proposed.

The third technology investigated is the combined cooling heat power (CCHP) technology. The CCHP system is designed to supply additional energy to the cooling load in a conventional CHP system [34]–[39]. Many studies on MES dealing with a cooling load are based on an absorption chiller (Ach) as a component of the EH to supply energy to the cooling load [40], [41]. In [42], the CCHP structure, including the Ach, is described, and an optimal hourly operation process for each component is proposed. An economic analysis comparing the CHP and CCHP techniques (payback period, discounted payback period, net present value, and benefit/cost methods) was presented in [43]. Further, in [44], a CCHP operation method based on biomass combustion was reported.

Among the three EH technologies described, the multi-energy outputs are represented by the input of electricity and NG. However, considering a broader analysis, an EH involving heat as the input can be configured by adding direct heat using wood or through a solar collector [45], [46]. Although three EH technologies were described, not all MESs or EHs of MESs contain these components, and none of the structures always operates independently. Alternatively, the design and components of the EH would vary according to its operation [47]. A representative MES was manufactured in [34] by separating the CHP and Ach.

Meanwhile, in [48], [49], hydrogen energy and HESS were interconnected with the CHP system. A combined MES and P2G system were presented in [50], and a method for using hydrogen as the energy for the MES was introduced. Representative examples of building an MES through an EH that includes all energy carriers associated with the structures described are provided in [51], [52].

Fig. 1 Shows the number of times CHP, CCHP and P2G technologies were used in previous studies. The media associated with the energy used when passing through each layer are illustrated separately. The three structures in Fig. 2 are represented by distinct colors, with the second- and third-layers showing the energy conversion representing the EH.

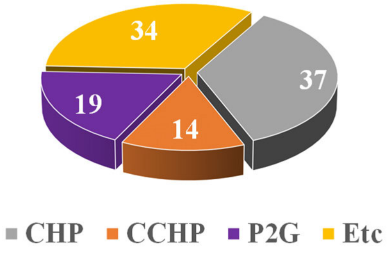

FIGURE 1. Diagram showing the number of different structures employed in energy hub models in previous studies [Table 4].

After presenting the MES configuration, its objective function is defined to solve the problem based on different perspectives. Many studies [100]–[125] have explored the economic improvements associated with the MES compared to conventional single systems [53], [54], [67]. Some other studies [131]–[140] proposed methods for enhancing the reliability of a system through the MES, and the simulation resulted in improved economic and reliability data compared to existing system. In the present study, the structure and objectives of the MES are examined. This investigation is divided into the following three parts:

In Section 2, the operational principles of existing single systems of different energy types are briefly described and previous studies are highlighted.

In Section 3, the EH concept is introduced and used to examine the conversion process for each single system energy type. The components of each energy system and previous studies are also reviewed.

Section 4 provides a description of the design process associated with the MES presented in Sections 2 and 3, with the objectives defined and benefits highlighted, and relating them to previous studies.

II. TRADITIONAL ENERGY SYSTEM

In this section the principles of different energy systems are reviewed. Flow analysis is performed for different components, including power, gas, and water. The flow and energy transfer equations for the energy storage systems (ESS), BESS, TES, IES, NGS, and HES are presented in Table 1. Fig. 2 shows the topology of an integrated MES, including the three EH technologies as input energy, energy conversion, and output energy layers.

TABLE 1. Energy carriers and the associated flow equations based on previous studies.

Energy carriers	Flow equation	Ref
Power	$P_i= \sum_{j=1}^{n} V_iV_j\,(G_{ij}Cos\theta_{ij}+B_{ij}Sin\theta_{ij})$[W] $Q_i= \sum_{j=1}^{n} V_iV_j\,(G_{ij}Cos\theta_{ij}-B_{ij}Sin\theta_{ij})$[Var]	Tao Wang. [63]
Gas	$Q_g=\frac{18.062T_b}{P_b}\sqrt{\frac{P_i^2-P_j^2}{\gamma_g\bar{T}\bar{z}(\frac{L}{D^{\frac{16}{3}}})}}$ [lb]	Hossein Amani. [54]
Water	$Q_w=\frac{P_j-P_i}{0.5\left(V_i^2-V_j^2\right)+g(y_i-y_j)}$ [kg/m^3]	Ruqiong Qin. [141]

A. POWER SYSTEM

Considering that this study examines electricity as the basis of the MES, knowledge of the structure and analysis of the power system is essential. Traditionally, many studies [21] use power flow that could be solved through Newton's method to analyze the system.

B. NATURAL GAS SYSTEM

The EH of the MES utilizes NG as one energy input. Although the NG handling and production methods differ by country and region, in most studies, the Weymouth equation is commonly used to analyze gas flow through pipes [53], [54]. Many other techniques in addition to the Weymouth equation exist for analyzing gas networks [55]–[58]. For example, in [59], gas flow in the Belgium gas system was analyzed based on the

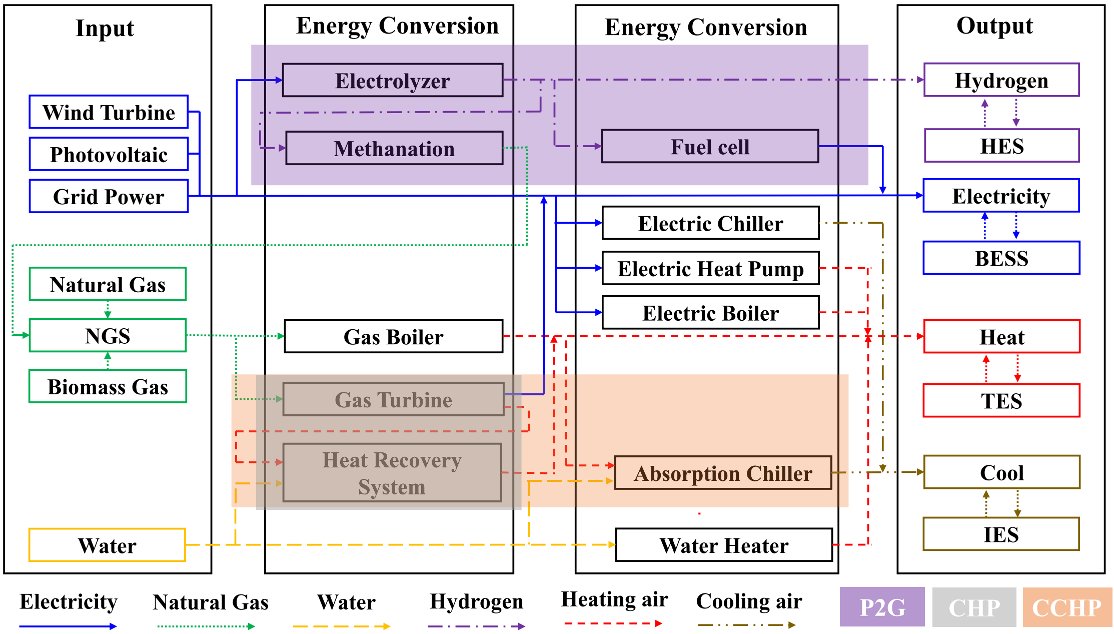

FIGURE 2. Conceptual model of a multi energy system [Table 5].

Newton–Raphson formulation. This paper considered the pressure drop in the gas system just as the voltage drop in the power system. In [60] the gas flow was calculated and analyzed using node and loop equations, with the analysis based on the method used in the power system analysis. This method considers the diameter and length of the pipeline, the absolute roughness, gas velocity, dynamic water viscosity, friction factor, and pressure drop.

C. THERMAL SYSTEM

According to previous studies on MES, heat serves as energy input and output [61], [62]. Although heat energy cannot be transmitted through cables (as in power systems) or flow through pipes, such as NG, the associated temperature can be transmitted through a medium, such as water and gas [64]–[67] In [64], [66], [67] flow analysis was conducted using water as the medium. The Bernoulli equation is used to analyze thermal system with water the medium.

D. ENERGY STORAGE SYSTEM

Single energy systems usually contain an ESS, whereas in the MES, the system stores power energy using a BESS, NG energy using an NGS, a TES for storing thermal energy, an IES for storing cooling energy, and an HES for storing hydrogen energy. Details on the BESS, NGS, TES, IES, and HES systems are available in [68]–[72].

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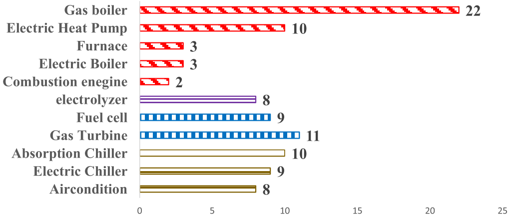


FIGURE 3. Different components for energy hub models were reported in previous studies [Table 6].

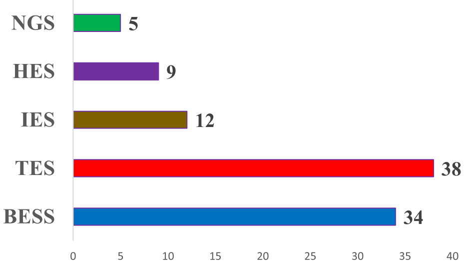


FIGURE 4. Energy storage systems and their usage frequency based on previous studies [Table 7].

III. MULTIPLE ENERGY CONVERSION SYSTEMS

In this section, the components of each energy conversion system are examined by introducing the EH concept. The MES coupling matrix expressed as the input energy variable $(x_1, x_2, \ldots, x_n)$ and output energy variables $(y_1, y_2, \ldots, y_n)$ following Eq. (1). The energy conversion in an EH through

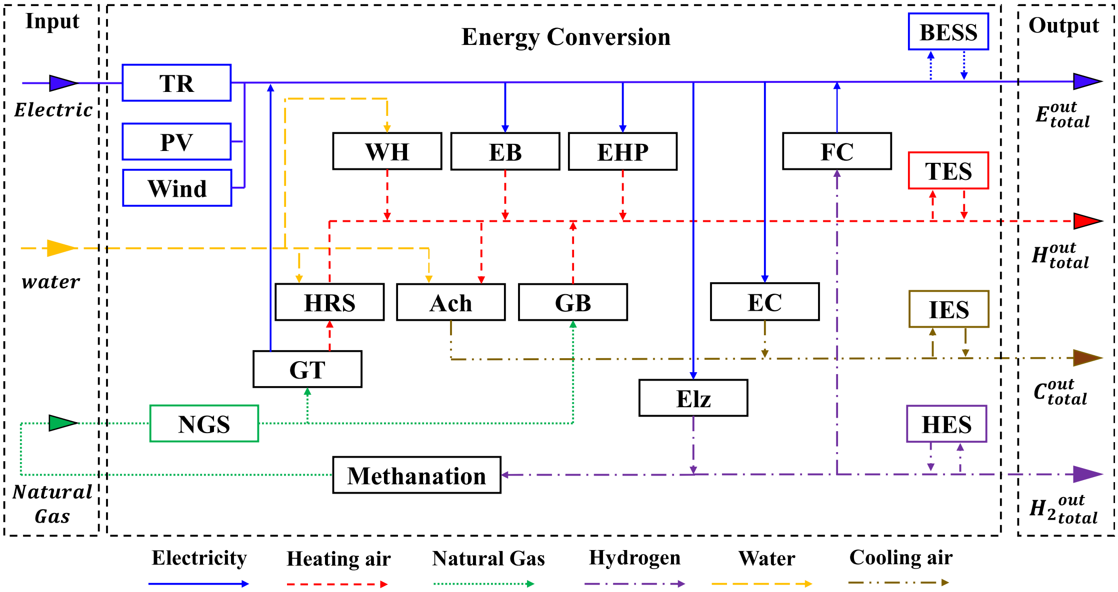


FIGURE 5. Illustration of the components of an energy hub and their links to the system [Table 5].

a coupling matrix similar to Eq. (1) is described in [73–75]. An example of a multi-EH system based on a coupling matrix is shown Fig.5, while the EH of the MES illustrated in Fig.6.

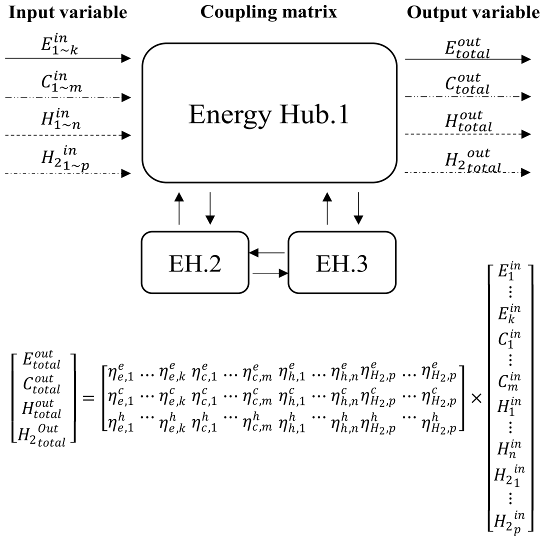
The energy conversion of the MES involving the EH is configured as a multi-energy to multi-energy system. This involves multiple inputs, such as electricity, NG, and thermal (water) in the EH and multiple outputs including electricity, heat, and cool air. The multi-energy to electricity (MEtE), multi-energy to heat (MEtH), multi-energy to cooling (MEtC), and multi-energy to hydrogen (MEtH2) systems were configured as displayed in Fig. 6. The frequency of each input and output energy in the studies reviewed are exhibited in Fig. 7, Fig. 8, Fig. 9 and Fig. 10 respectively, while the EH representation for each output energy is displayed in Fig. 6.

A. MULTI-ENERGY TO ELECTRICITY

In Figs 4 and 6, the CHP and P2G structures represent the MEtE system, with the CHP outputting electricity using gas as the input of a GT. In case of an emergency of the power system or in order to implement optimal electricity supply according to the time of use (TOU) fee, multi energy shall be converted into electricity and used. Linear modeling of the GT using NARMAX is available in [76]. Conversely, in the P2G structure, electrical power is generated with hydrogen as the input using an FC. The basic operating principle and output expression of the FC are provided in [77].

B. MULTI-ENERGY TO HEAT

As shown in Figs. 4 and 6, the CHP structure involves the MEtH system. The components of this structure supply thermal energy through the HRS from the heat loss generated when the GT in the CHP structure is operated [78]. Because the supply of heat energy through CHP uses waste heat, it is



$$\begin{bmatrix} E_{total}^{out} \\ C_{total}^{out} \\ H_{total}^{out} \\ {H_2}_{total}^{Out} \end{bmatrix} = \begin{bmatrix} \eta_{e,1}^{e} \cdots \eta_{e,k}^{e}\ \eta_{c,1}^{e} \cdots \eta_{c,m}^{e}\ \eta_{h,1}^{e} \cdots \eta_{h,n}^{e}\eta_{H_2,p}^{e} \cdots \eta_{H_2,p}^{e} \\ \eta_{e,1}^{c} \cdots \eta_{e,k}^{c}\ \eta_{c,1}^{c} \cdots \eta_{c,m}^{c}\ \eta_{h,1}^{c} \cdots \eta_{h,n}^{c}\eta_{H_2,p}^{c} \cdots \eta_{H_2,p}^{c} \\ \eta_{e,1}^{h} \cdots \eta_{e,k}^{h}\ \eta_{c,1}^{h} \cdots \eta_{c,m}^{h}\ \eta_{h,1}^{h} \cdots \eta_{h,n}^{h}\eta_{H_2,p}^{h} \cdots \eta_{H_2,p}^{h} \end{bmatrix} \times \begin{bmatrix} E_1^{in} \\ \vdots \\ E_k^{in} \\ C_1^{in} \\ \vdots \\ C_m^{in} \\ H_1^{in} \\ \vdots \\ H_n^{in} \\ {H_2}_1^{in} \\ \vdots \\ {H_2}_p^{in} \end{bmatrix}$$

FIGURE 6. Illustration of a multi-energy hub and coupling matrix.

much more efficient than the supply through other energy. Regarding the components, the gas boiler (GB) outputs heat from the gas input, while the EHP and EB output heat from the electricity input, and the water heater (WH) outputs heat from the water input [79]–[82].

C. MULTI-ENERGY TO COOLING

The CCHP structure in Figs. 4 and 6 represent the MEtC system, and this involves interoperation of the GT and HRS components. The hot water generated in the HRS using the waste heat of the GT is supplied to the Ach, and cooling energy is provided by boiling and evaporating water at approximately 5°C. In addition, an electric chiller (EC) is used for cooling the output from the electricity input [83], [84].

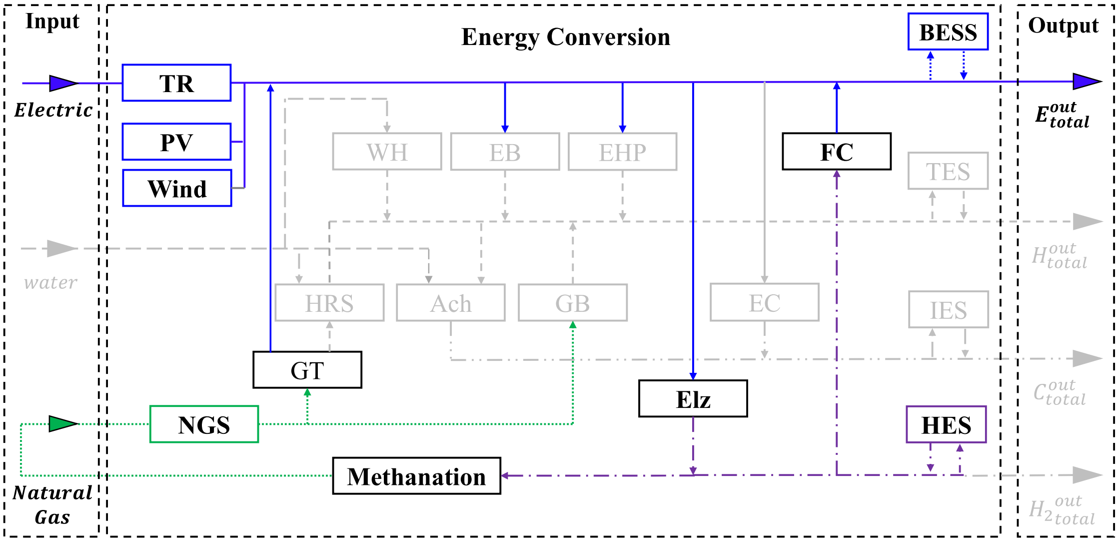


FIGURE 7. Illustration of the multi-energy to electricity system in energy hub [Table 5].

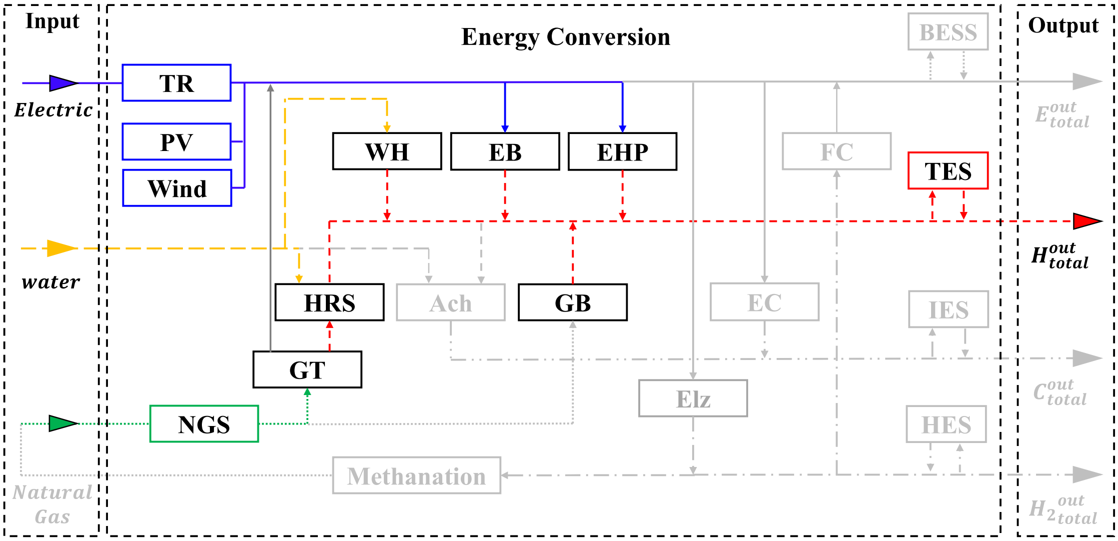


FIGURE 8. Illustration of the multi-energy to heat system in energy hub [Table 5].

Generally, cooling energy is supplied through electricity, but using CCHP to operate the Arch is more efficient than other energy sources because it utilizes waste heat just like CHP's heat supply.

D. MULTI-ENERGY TO HYDROGEN

In Figs. 4 and 6, the P2G technology is employed as an MEtH2 system. This technology is closely associated with the utilization of hydrogen, and the hydrogen system is described in detail in [87]. In the present study, the P2G structure involves a closed circuit, as shown in Fig. 10. This means that the P2G system is not restricted to supplying hydrogen to the load, but is flexible in the system operation compared to existing systems. A system operation involving the P2G system proposed by [85] is described subsequently. First, if the energy of the power system is balanced, the P2G system does not operate. Second, if surplus power is generated by a renewable energy source, the hydrogen energy is stored in the HES through the Elz [88], [89] Third, if the energy supply is insufficient, the hydrogen energy is converted to electrical energy and supplied to the electrical system through the FC. The hydrogen production process using the P2G system and details of the methanation are described in [86], while details of the hydrogen system are available in [87].

E. MULTI-ENERGY ANALYSIS

Although the supply of heat and cooling energy through CHP and CCHP is determined according to each energy demand, hydrogen energy using P2G technology is often used to increase energy utilization depending on the degree of

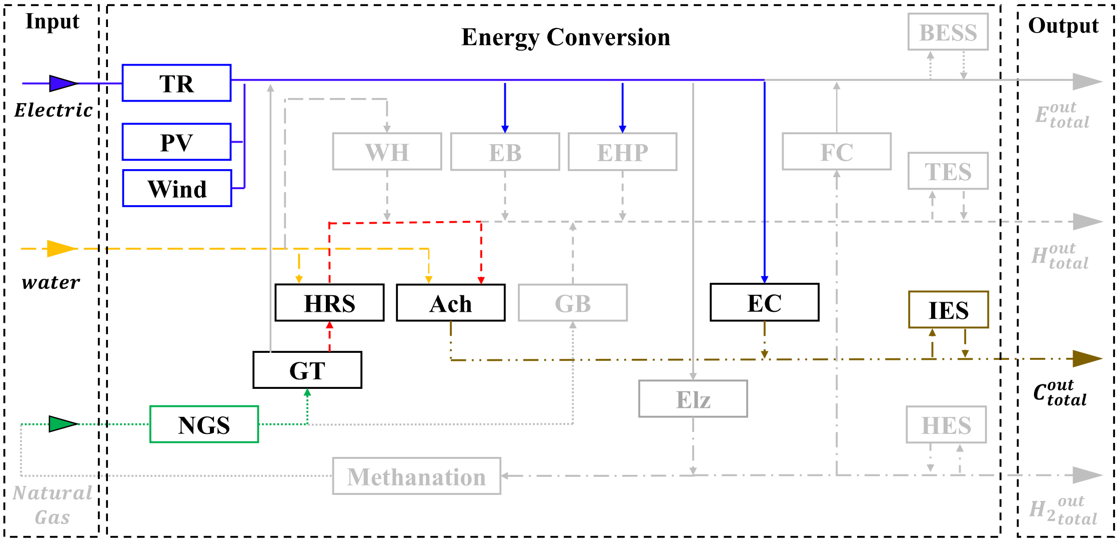


FIGURE 9. Illustration of the multi-energy to cooling system in energy hub [Table 5].

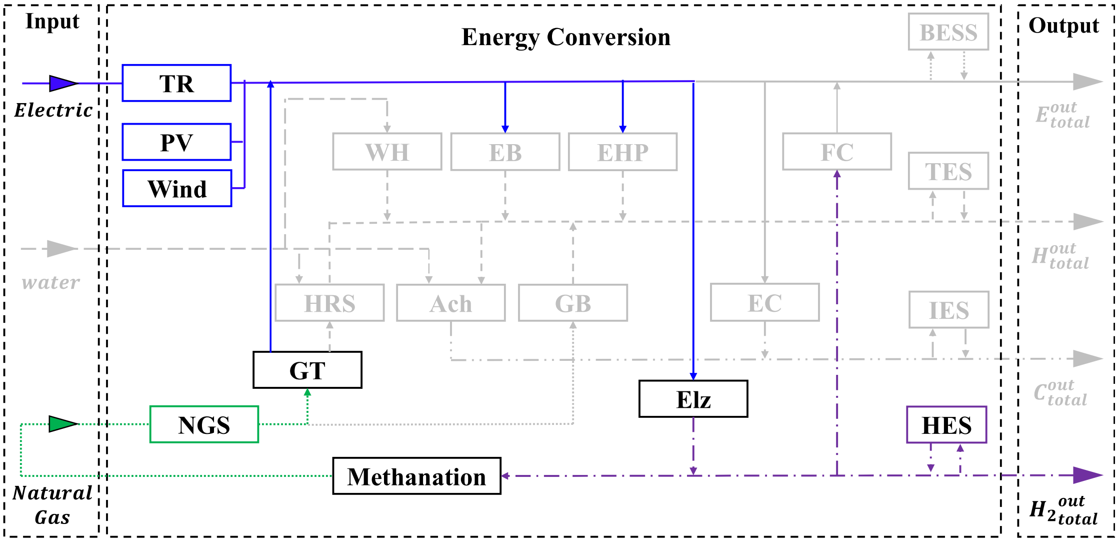


FIGURE 10. Illustration of the multi-energy to hydrogen system in energy hub [Table 5].

renewable energy use without being affected by hydrogen load. Therefore, the energy produced depends on the final operational purpose and the reference papers investigated in this study show that the most frequent multi-energy to heat systems are constructed based on CHP, which can be used to supply heat energy.

IV. MULTI-ENERGY SYSTEMS OBJECTIVES

The objective of constructing a MES is to provide and energy system with an environmentally-friendly power generation. This involves increasing the efficiency of the surplus power generated by a renewable energy source while reducing the underlying power generation. Although MES are developed to improve the efficiency of an energy system, economic inefficiency would invalidate its utility. Therefore, many studies have attempted to configure the MES topology and demonstrate the associated optimized economics in terms of capacity and operation of its components to enhance its reliability compared to existing systems.

A. ENERGY ECONOMY EFFICIENCY OF THE MULTI-ENERGY SYSTEM

One significant advantage of using multiple energy sources is that it is economical. In many countries, the electricity rates change with time. Therefore, the rate during a high-demand period differs from that in a low-demand period [90]. Also, changes in gas rates in the gas market differ from rates in the electricity market. In [91], the economics of the MES was analyzed after incorporating the gas market into the existing electricity market as the base and vice-versa. According

TABLE 2. Summary of data for different optimization technique reported in existing studies.

Reference	EH Structures	Optimization Techniques	ESS	Objective
Asif K. [85]	P2G	TLBO, Jaya algorithm, TACMA	HES	Total annual cost minimization
Minglei B. [101]	P2G	MILP	NGS	Gas network reliability analysis
Tao Wang. [63]	CHP	MILP	BESS, TES, IES	Total annual cost minimization
Eduardo A. [92]	CHP	MILP	TES	Total import energy price minimization
Da xu. [102]	CHP	ADMM, MISOCP, Lagrange Multiplier	BESS	Total annual cost minimization
Thanh-Tung H. [47]	CCHP	BONMIN	BESS, TES, IES	Total a day cost minimization
Yongli W and Yudong W. [103]	CCHP	FOA	BESS, TES	Total annual cost minimization
Tengfei M. [96]	CCHP	MILP	BESS, TES, IES	Total import energy price minimization
Thanhtung HA and Youjun Z. [40]	CCHP	BONMIN	BESS	Total a day energy costs minimization
Xiangping C. [104]	P2G	GA	HES	Find optimal HES SOC
Mingli Z and Na Z. [50]	P2G	MILP	HES	Total annual cost minimization
A Shahmohammadi. [93]	CHP	MILP	BESS, TES	Total annual cost minimization
Yanhong L. [97]	CCHP	MILP	BESS, TES	Total import energy price minimization
Liting T. [24]	CHP	Lagrange multiplier, MILP	BESS, TES	Minimization equivalent multi-energy consumption
Wujing H. [73]	CHP	MILP	TES, IES	Total annual cost minimization
Di Liu. [23]	CCHP	Kriging	BESS, TES, IES	Total annual cost minimization
Amirhossein D. [105]	CHP	MILP	BESS, TES	Total annual cost minimization
Enrico F. [46]	CCHP	GRG		Total benefit maximization
Aras S. [37]	CCHP	NLP	TES	Total benefit maximization
Sijia G. [49]	P2G	LP	HES	Total operation cost minimization
Mohammadreza. [25]	CCHP	MILP	BESS, TES	Total a day Cost minimization
Wujing H. [106]	CHP	MPLP, LP	TES, IES	Load curtailment minimization
You Xue and Ying Gao. [16]	P2G	IPM	NGS	Total annual cost minimization
Rui Li. [26]	CHP	MILP	BESS, TES	Total profit maximization
Majid M and Kazem K. [95]	CHP	MILP	BESS	Total import energy price minimization
Pengfei Z. [107]	CHP	CGA	BESS	Total import energy price minimization
Mahmoud-Reza H. [62]	CCHP	MILP	TES	Total operation cost minimization
Cuo Zhang. [108]	CCHP	C&CG	TES	Total profit maximization
Yibo J and Jian X. [109]	CCHP	MILP	TES, IES	Total import energy price minimization
Tao Guo. [110]	CHP	Kuhn-Tucker		Total annual cost minimization
A. Vasebi. [111]	CHP	HS, GA		Total power production cost minimization
Lu Zhang. [31]	CHP	MILP	TES	Total import energy price minimization
Tianhao L. [100]	CCHP	MILP	BESS, TES	Total operation cost minimization
Da Huop. [112]	CHP	EVPI, VSS	TES	Total generation cost minimization
Alessandra P. [113]	CHP	RO	BESS, TES	Total operation cost minimization
M.J. Vahid-Pakdel. [114]	CHP	MILP	BESS, TES	Total operation cost minimization
Mohammad R. [115]	CHP	MIP		Total customer payment minimization
Chatelain T. [116]	CHP	PSO	BESS, TES	Total operation cost minimization
Xinhui Lu. [117]	CHP	RO	TES	Total operation cost minimization
Hanchen Z. [118]	CHP	PSO		Optimal energy hub expansion
Mads R. [119]	CHP	MPOD	TES	Total operation cost minimization
Mehrdad A. [120]	CHP	A new EH operation optimization	BESS, TES	Total operation cost minimization
Mahmoud R. [121]	CCHP	SO	BESS	Total operation cost minimization
A Parisio. [122]	CHP	RO	BESS, TES, HES	Total operation cost minimization
Vahid D. [123]	CHP	SO	BESS	Total import energy price minimization
Yu Huang and Weiting Z. [124]	CCHP	PSO	TES	Total import energy price minimization
Farah J. [125]	CHP	MIP	BESS, TES	Total import energy price minimization

*TLBO : Teaching learning-based optimization, TACMA: Total annual cost minimization algorithm, MILP: Mixed integer linear programming, ADMM: Alternating direction method of multipliers, MISCOP: Mixed integer second-order cone programming, BONMIN: Basic open-source nonlinear mixed-integer programming, FOA: Fruit fly algorithm, GA: Genetic algorithm, GRG: Generalized reduced gradient method, NLP: Nonlinear programming, LP: Linear programming, IPM: Interior point method, CGA: Compact genetic algorithm, C&CG: Column and constraint generation, EVPI: Expected value of perfect information, VSS: Value of the stochastic solution, RO: Robust optimization, MIP: Mixed integer programming, PSO: Particle swarm optimization, MPOD: Multi-period optimal dispatch, SO: Stochastic optimization, HS: Human Strategy.

TABLE 3. Summary of reliability indexes used in existing studies.

Reference	Reliability Index									
	MAIFI	SAIFI	SAIDI	LOLP	LOGP	LOLE	LOEE	EENS	EGNS	ASAI
Ziyu Z. [15]			✓			✓				
Minglei B. [101]				✓	✓			✓	✓	
Amirhossein D. [105]						✓		✓		
Zhonghua C. [131]										✓
M Moeini Aghtaie. [132]			✓					✓		
Gaudenz K. [133]								✓		
Shaoyun GE. [134]			✓				✓			
Mehrdad Setayesh N. [135]	✓	✓	✓							
Xiandong Xu. [136]								✓		
Sheng. [137]								✓	✓	
Chuan WANG. [138]						✓				
Gaudenz K. [139]								✓		
Minglei B. [140]				✓	✓			✓	✓	
Youbo Liu. [48]		✓						✓		

*MAIFI: Momentary Average Interruption Frequency Index, SAIFI: System Average Interruption Frequency Index, SAIDI: System Average Interruption Duration Index, LOLP: Loss of Load Probability, LOGP: Loss of Gas-load Probability, LOLE: Loss of Load Expectation, LOEE: Loss of Energy Expectation, EENS: Expected Energy Not Supplied, EGNS: Expected Gas Not Supplied, ASAI: Average Service Availability Index

to [92], economic efficiency can be improved by utilizing a different energy source through energy conversion instead of purchasing electricity from the power market during peak times. Therefore, many studies on the MES maximize the economic benefits through optimal operation, with the cost function as the objective function. The two elements in the cost function utilizing independent facilities include the operation and investment costs. However, in [93], [94], the capital recovery rate is included in the cost function to accommodate the facilities' interest rate and life span. In some studies, the ToU rate is also added to the pricing information [95]. In [96], the ToU system was compared with a real-time price (RTP) system. The cost function advanced by [97], [98] produce better results by considering the economic benefits associated with pollutants emission reduction compared to the cost function relying on the investment and operation costs. To analyze the economics of a system with additional independent components in the energy supply through the main grid, mathematical optimization involving analyzing the power generation cost according to the life, capacity, and power generation time of the individual components is necessary. Different optimization techniques have been employed to identify the optimal point associated with the maximum or minimum values of an objective function with multiple variables [99]. In [100], a method for optimal configuration of an EH and an algorithm for converting a complex EH model to a multi-EH model was proposed. A summary of the optimization techniques, EH structures, ESSs, and objective function reported previous studies are presented in Table 2.

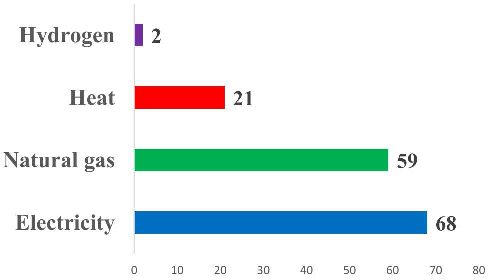


FIGURE 11. Plot showing input energy types reported in previous studies [Table 5].

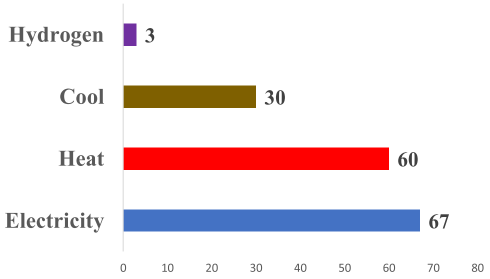


FIGURE 12. Representation of energy output types reported in previous studies [Table 5].

B. MULTI-ENERGY SYSTEM RELIABILITY

The power system can experience internal overload and facility problems as well as failures due to lightning and other external causes. The power system failure is defined based on the failure probability, while its standard reliability is analyzed based on the damage caused by failures. Reliability engineering can also be employed in gas systems. In [126], the failure rate was analyzed according to the demand and supply of the gas system using Monte Carlo simulation. In [127], the reliability of the heat supply source in a thermal system, including an HES, was analyzed. Reliability indexes used for evaluating the impact of power failures and interruptions in a power system include the system or customer average interruption frequency index (SAIFI, CAIFI), system or customer average interruption duration index (SAIDI, CAIDI), energy not supplied (ENS), and expected customer outage cost (ECOST) [128], [129]. In [130], an approach for conducting a reliability evaluation for an MES was introduced. The reliability indexes used in previous studies are presented in Table 3. These reliability indexes are objective and are associated with natural gas grids. The LOGP and EGNS reported in [15] and the LOGLP and EGNS reported in [101] represent the annual probability of gas supply interruption and the yearly amount of unsupplied gas linked to supply interruptions. Based on the power system and gas system reliability indices shown in Table 2, the integrated reliability of MES by external and internal factors can be analyzed, and stability analysis through future research by MES can be performed based on the derived reliability determination.

V. CONCLUSION

In this study, we have examined several single energy systems that are commonly used for constructing an MES. The MES topology was configured based on the EH concept and energy conversion. The economics and reliability associated with the MES were analyzed by mathematical modeling based on a coupling matrix. The high efficiency of the MES operation has been validated in many studies. Because the power generation of renewable energy is predicted by a probability distribution, a power system with reserve power requirement inevitably generates surplus power. To solve the problem, flexibly managing different types of energy sources (electricity, NG, and heat) is the best option. As a result, each country or region can establish a more efficient energy operation strategy that ultimately promote environmentally-friendly power systems and reduce pollutant emissions. Such approach will contribute to the energy sustainability in a green world. In future research, we will examine the MES based on the perspectives of the P2G and G2P systems, specifically the former, which is currently of interest worldwide. An optimal energy operating system incorporating reliability and economics for each system will be considered.

APPENDIX

TABLE 4. Fig [1] references.

EH structures	References
CHP	[4], [7], [9], [20], [21], [25], [26], [28], [32], [39], [40], [41], [47], [48], [49], [51], [55], [57], [60], [61], [76], [77], [79], [80], [110], [111], [127], [128], [129], [130], [131], [132], [133], [134], [135], [137], [138]
CCHP	[29], [31], [33], [34], [36], [43], [45], [52], [64], [71], [72], [75], [136], [139]
P2G	[2], [5], [6], [8], [9], [11], [13], [16], [17], [30], [32], [36], [38], [43], [77], [88], [89], [138], [140]

TABLE 5. Fig [2], [5], [7]–[12] references.

Energy conversion mode	References
Multi energy to electricity	[2], [3], [4], [5], [6], [7], [8], [9], [10], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [25], [26], [27], [28], [29], [30], [31], [32], [33], [36], [37], [38], [39], [40], [41], [43], [45], [46], [47], [48], [49], [51], [52], [55], [56], [59], [60], [61], [62], [64], [71], [75], [86], [127], [128], [129], [130], [132], [133], [134], [135], [136], [137], [138], [139], [140]
Multi energy to Heat	[4], [9], [10], [12], [13], [14], [15], [17], [18], [19], [20], [21], [23], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [36], [37], [39], [40], [43], [45], [46], [47], [48], [49], [51], [52], [55], [56], [59], [60], [61], [62], [64], [71], [72], [75], [86], [127], [128], [129], [130], [131], [132], [133], [134], [135], [136], [137], [138], [139], [140]
Multi energy to Cooling	[4], [10], [12], [13], [14], [15], [19], [21], [23], [25], [26], [27], [28], [29], [30], [31], [32], [36], [40], [43], [45], [62], [64], [71], [72,] [131], [134], [136], [140]
Multi energy to Hydrogen	[17], [14], [137]

TABLE 6. Fig [3] references.

EH components	References
Gas boiler	[8], [32], [35], [40], [42], [45], [46], [47], [51], [62], [63], [92], [93], [96], [95], [96], [97], [102], [105], [117], [123], [125]
Electric heat pump	[20], [26], [39], [49], [73], [79], [92], [103], [106], [123]
Furnace	[18], [61], [102]
Electric boiler	[46], [50],[73]
Combustion engine	[23], [63], [73]
Electrolyzer	[8], [10], [16], [18], [49], [50], [85], [104],
Fuel cell	[10], [16], [18], [49], [50], [77], [85], [104], [122]
Gas turbine	[18], [35], [36], [38], [42], [47], [61], [96], [97], [103], [109]
Absorption chiller	[23], [34], [35], [36], [42], [47], [62], [108], [109], [134]
Electric chiller	[23], [35], [45], [46], [63], [73], [96], [97], [105]
Air-condition	[40], [42], [47], [95], [96], [97], [103], [134]

TABLE 7. Fig [4] references.

Energy Storage	References
BESS	[4], [9], [10], [12], [13], [15], [17], [18], [19], [20], [23], [25], [29], [32], [33], [36], [45], [47], [48], [49], [52], [56], [60], [71], [86], [100], [128], [129], [131], [135], [136], [137], [138], [140]
TES	[4], [7], [10], [12], [13], [14], [18], [19], [20], [21], [23], [25], [29], [31], [33], [36], [41], [45], [47], [52], [56], [64], [71], [72], [75], [86], [91], [100], [127], [128], [129], [131], [132], [134], [135], [137], [139], [140]
IES	[4], [10], [13], [21], [23], [36], [41], [45], [46], [52], [63], [75]
HES	[2], [14], [16], [17], [30], [32], [38], [77], [137]
NGS	[3], [6], [14], [43], [84]

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