ISSN: 2251-9246
EISSN: 2345-6221

pp. 143:148

Smart Management of Pollution in the Integrated Energy Systems

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Abstract

Today, energy carriers are addressed as one of the main pillars of energy generation due to the increased growth of industries in developed and developing countries. According to the global view, increased consumption of energy carriers has increased the production of greenhouse gases, the global average temperature, resulting in the faster melting of ice in Antarctica. Moreover, increased pollution due to consumption of fossil fuels for electricity generation is causing numerous problems for industrial cities, photochemical smog, and numerous lung diseases for humans and often living organisms. Due to the above reasons, using methods to minimize energy carriers consumption and applying renewable energy in order to reduce the extent of generated pollution is highly important. Using integrated energy systems (IES) might help manage energy resources properly and minimize the extent of pollution. This article has proposed a smart management system of an energy hub that includes an input (consisting of fossil fuels, renewable energy, and electricity grid) and output (consisting of consumers). The proposed system can manage energy carries and maximize the use of renewable energies, and it can absorb high levels of generated CO2 and transform it to gas energy carries in addition to save energy. Such an approach has reduced CO2 level and its derivatives inside the energy hub, and reduced the total cost of the system and this is because a part of gas fuel needed by the system is supplied. This article has shown that using such a system reduces the cost imposed by system pollution by 9.08% and the total cost of the system by 13.57%.
Keywords: Integrated energy system; Smart pollution management; Renewable energy; Methane reformer
Article history: Received 29-Jan-2020; Revised 19-Feb-2021; Accepted 02-Mar-2021.

1. Introduction

With the development of industries and the ever-increasing requirement for energy carriers as raw materials for generating energy, many of the industrial communities have encountered an increase in environmental pollution and the generation of greenhouse gases. On the other hand, energy carriers play a significant role in the prime cost of the generated energy. Increasing concerns about global warming, melting of polar ice caps, and shortage of global energy resources, an approach has been presented to reduce pollution and optimize energy consumption and the full cost of the industries.

In [1] it demonstrates the process and economic viability of a new production route for methanol utilizing captured CO_2 and H2 produced from renewable, photocatalytic water splitting. The important point about [2] is that to generate zero pollution, in addition to the wind farm, geothermal plant and solar furnace for providing the required heat play an essential role in reducing the network pollution. In [3], a robust method has been presented to optimize the energy hub using the uncertainty of the renewable resources, load, and electric vehicle. Due to using electric vehicles and reducing the dependency on the combined heat and power generation system, electrolyzer should be used. Also, in this paper, if storage is used, the system efficiency increases. Considering the price uncertainty, ESS might increase the price increase concern. In [4], a power grid system has a renewable wind power plant with uncertainty connected to electric vehicles and a combined heat and power production system in which the electricity price is considered as uncertain; in addition, this grid has the islanding capability. In this article, the solar power plant has not been considered along with uncertainty; in addition, due to the presence of electric vehicles, the connection of electrolyzer provide significant assistance in supplying the energy of the vehicle from clean energy resources that have not been considered.

The input of the energy hub considered in this study is natural gas, electricity, fuel oil, and wind and solar renewable energies in which uncertainty is considered. The consumers' load is also estimated through examining the energy consumption in the past as uncertainty. This system includes five electrical, thermal, water, Hydrogen, and methane storages. In the energy hub, transformer, combined heat and electricity generation system, thermal furnace, electrolyzer, and methane reformer are used. This paper shows that using storage and using methane reformer simultaneously reduces the pollution caused by CO_2 and CHP and using the methane production process, and the power generation cost is reduced by 13.57%. The objective function equations are nonlinear and optimized using GAMS25.1.2.

2. Methodology

2.1 . Hub physical model

Figure (1) shows the studied energy hub. The electric power taken from the network is the CHP electric power, the wind and solar powers are the electric inputs of the system. At low load hours or when the energy carrier prices are low, the ESSs are charged, and the additional generated power enters the electrolyzer, and Hydrogen is produced. The Hydrogen enters the hydrogen storage. This Hydrogen enters the refer to produce methane and water with the CO_2 taken from the output of the thermal furnace and the CHP, and the produced methane enters the methane storage to supply a part of the gas required by the CHP. The power generated by the thermal furnace and thermal power of the CHP are the thermal inputs of the system.

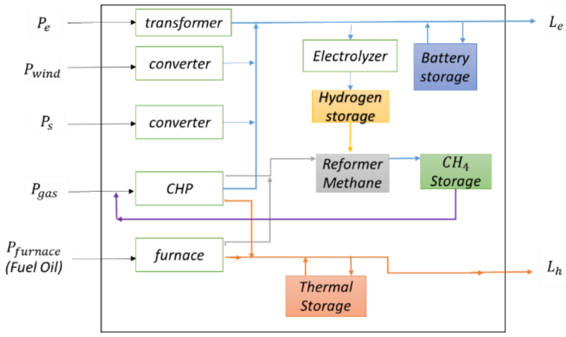

Fig. 1. The desired integrated energy system

2.2. Mathematical Model of Hub

Eq. (1) describes the relationship between the input and output of the energy hub. The power generated by each component of the energy hub has some constraints considering the application of the hub and the connections of its internal components, which should be considered for hub optimization. These constraints are given in Eqs. (2) to Eq. (7). Also, in the subsequent sections, the constraints of the storage and energy converters are given.

$$\begin{bmatrix} L_e(t) \\ L_h(t) \end{bmatrix} = \begin{bmatrix} Ne & N_{pv} & N_{wind} & N_{chpe} \\ 0 & 0 & 0 & N_{chph} \end{bmatrix} \begin{bmatrix} P_{elc}(t) \\ P_s(t) \\ P_{wind}(t) \\ P_{CHP}(t) \end{bmatrix} + \begin{bmatrix} ESS(t) \\ TES(t) \end{bmatrix} \quad (1)$$

where Ne is the efficiency of the transformer to transmit power from the transmission line, N_{pv} is the efficiency of power generated by solar panels, N_{wind} is the efficiency of power generated by wind turbines, N_{chpe} is the efficiency of electric power generated by combined heat and power systems, N_{chph} is the efficiency of thermal power generated by combined heat and power systems, $P_e(t)$ is the input power of transmission line, $P_s(t)$ is the input power of solar power station, $P_W(t)$ is the input power of wind power station, $P_g(t)$ is the input power stemmed from burning gas inside combined heat and power systems, and $P_h(t)$ is the thermal power stemmed from burning gas inside the above furnace. ESS stands for electric energy storage and TES stands for thermal energy storage. Also, the following conditions are applied to integrated energy system:

$$0 \le P_{g\,Electrical}(t) \le N_{chpe}.P_{g\,max}(t) \quad (2)$$

$$0 \le P_{g\,heat}(t) \le N_{chph}.P_{g\,max}(t) \quad (3)$$

$$0 \le P_s(t) \le N_{pv}.P_{s\,max}(t) \quad (4)$$

$$0 \le P_w(t) \le N_{wind}.P_{w\,max}(t) \quad (5)$$

$$0 \le P_h(t) \le N_h.P_{h\,max}(t) \quad (6)$$

$$0 \le P_e(t) \le N_e.P_{e\,max}(t) \quad (7)$$

Eq. (8) describes the electrical power of the ESS at time t, which is equal to energy remaining at t-1 plus the difference of the charge and discharge at time t. Eqs. (9) to Eq. (12) represent the charge/discharge constraints, capacity, the relationship between input and output of the electrical storage with electrical load. The values considered for ESS are given in Table 1. [5]

$$ESS(t): \quad SOC_t = SOC_{t-1} + \left(P_t^c \eta_c - \frac{P_t^d}{\eta_d}\right)\Delta_t \quad (8)$$

$$\text{Constraints}: \; P_{min}^c \le P_t^c \le P_{max}^c \quad (9)$$

$$P_{min}^d \le P_t^d \le P_{max}^d \quad (10)$$

$$SOC_{min} \le SOC_t \le SOC_{max} \quad (11)$$

$$\textstyle\sum_g P_{g,t} + P_t^d \ge L_e - P_t^c \quad (12)$$

Eq. (13) describes the thermal power of TES at time t, which is equal to the energy remaining from t-1 plus the difference of the thermal energy charge and discharge at time t. Eqs. (14) to Eq. (17) represent the charge/discharge constraint, capacity, the relationship between input and output power of the thermal storage with thermal load. The values considered for TES are given in Table 1.

$$TES(t): \quad TH_{t+1} = TH_t + \left(\eta_{ch} P_t^{ch} - \frac{P_t^{dch}}{\eta_{dch}}\right)\Delta_t \quad (13)$$

$$\text{Constraints}: \; P_{min}^{ch} \le P_t^{ch} \le P_{max}^{ch} \quad (14)$$

$$P_{min}^{dch} \le P_t^{dch} \le P_{max}^{dch} \quad (15)$$

$$TH_{min} \le TH_t \le TH_{max} \quad (16)$$

$$\textstyle\sum_g P_{g,t} + P_t^{dch} \ge L_h - P_t^{ch} \quad (17)$$

The values related to TES and ESS are presented in the table 1:

Table 1. The data for ESS and TES

ESS parameter	*Value*	*TES parameter*	*Value*
SOC_0	100	TH_0	100
SOC_{max}	300	TH_{max}	300
P_{max}^d	0.2 SOC_{max}	P_{max}^{dch}	0.2 TH_{max}
P_{min}^d	0	P_{min}^{dch}	0
P_{max}^c	0.2 SOC_{max}	P_{max}^{ch}	0.2 TH_{max}
P_{min}^c	0	P_{min}^{ch}	0
η_c	95%	η_{ch}	95%
η_d	90%	η_{dch}	95%

2.2.1. Modelling Hydrogen Production

As the key energy carrier, Hydrogen plays an essential role in power generation and generating gas carriers. From the economic point of view, to produce the required Hydrogen, the additional power generation of the wind and solar system (the excess electric power after responding to the electric load) is used to produce Hydrogen inside the electrolyzer. The electrolyzer required water and electric power to produce Hydrogen and it's shown in Fig. 2.
Water, as the main material in hydrogen production, plays an essential role in the energy hub. To produce Hydrogen in the electrolyzer, water is required. The inputs of the hub supply a part of the water, and the other part is supplied by the power generation chemical processes of the process of producing methane inside the reformer

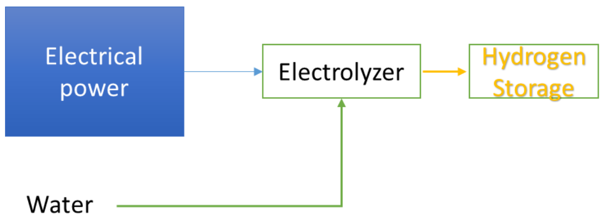

Fig. 2. hydrogen production systems

Eq. (18) shows the level of stored hydrogen. As mentioned in [6], the amount of energy required to produce 1 Kg of hydrogen with the aid of an electrolyzer equals 41.97 Kwh. According to Eq. (19), the amount of hydrogen required by a methane reformer in order to produce 1 Kg of methane equals 0.1815 Kg. [6]

$$HSC(t) = HSC(t-1) + HPE(t) \times etah_E - HUFC(t) - HUMR(t) \quad (18)$$

ISSN: 2251-9246
EISSN: 2345-6221

2.2.2. Modelling Methane Production

In recent years, methane reform has been used to convert methane to Hydrogen. Another application of methane reform is to convert Hydrogen to methane, which is not cost-effective because it requires high temperatures to carry out the chemical reactions. With the development of technology and using new catalyzers have used methane reformers at low temperatures cost-effectively; an instance of using these reformers is in space crafts and stations that is shown in Fig. 3. Thus, methane reformers can be used in the energy hub. The output of burning the furnace oil and the CHP output have various combinations that pollute the environment. One of these combinations is CO_2.

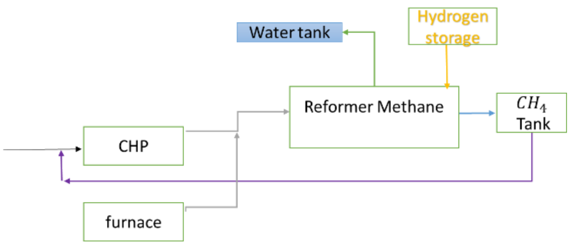

Fig. 3. Methane Production System

Considering Eq. (19), it can be observed that the output of the equation produces methane gas as the main source of energy production. Moreover, since this amount of CO_2 is considered as pollutant, the system fine coefficient decreases by absorbing this substance. Meanwhile, the output of the the reformer is also water and can fill the water tank. Considering the molar capacity of CO_2 and H_2 (g/mole), the ratio of the composition of these two substances is calculated and hydrogen is used according to the amount of absorbed CO_2 (g). On the other hand, considering Ref. [7], the production capacity of CO_2 in CHP is according to Equation (23), which is 116.9 pounds per MMBTU that is 0.18 kilogram per kilowatt hour by converting to SI system; the methane reformer production efficiency is 80, that by calculating the heat capacity of methane, the system's methane production capacity is 15.2 kWh/kg. According to Ref. [8], for each liter of furnace fuel, 11.84 kWh of energy is produced and emits 3.178 kg of carbon dioxide, which is equivalent to 0.268 kg of carbon dioxide per kilowatt hour.

$$CO_2 + 4H_2 = CH_4 + 2H_2O \tag{19}$$

2.2.3. CO_2 Absorption model

The level of absorbed CO_2 (ACA as shortened form) by CHP output and heat furnace (with fuel oil) is shown in Equation (20). According to the molecular mass of each component of Equation (19), an amount of 0.3645 Kg of methane gas is produced per 1 Kg of input CO_2 to the reformer and by taking into account 0.96 of reformer efficiency. The power produced by methane consumption ($P_{inj}(t)$) in the system is calculated to be 5.326 times the absorbed CO_2.

$$ACA(t) = 0.8 \times (0.181\left(\frac{Kg}{Kwh}\right) \times P_{gas}(t)(Kwh) + 0.268\left(\frac{Kg}{Kwh}\right) \times P_{Furnace}(t)(Kwh)) \tag{20}$$

Tables 2 and 3 shows the values considered for the simulation with the aid of GAMS and MATLAB software.

Table. 2. The System Modelling Parameters

$\boldsymbol{Ne}$	0.9	a	1
N_{pv}	0.8	b	12
N_{wind}	0.7	c	0.12
N_{chpe}	0.4	α	3
N_{chph}	0.35	β	5
Nh	0.95	γ	0.5
$\boldsymbol{E_{stb}}$	150	$\boldsymbol{e^-_{e\ discharge}}$	0.9
h_{stb}	150	$e^+_{h\ charge}$	0.98
$P_{e\ max}$	800	$e^-_{h\ discharge}$	0.98
$P_{g\ max}$	1800	V^c_{in}	4
$P_{h\ max}$	800	V^c_{out}	30
$e^+_{e\ charge}$	0.95	V_{rated}	15
$\boldsymbol{S_r}$	1000	$\boldsymbol{S_r}$	1000
$P_{S-rated}$	50	$P_{S-rated}$	50
Fuel cost	6	*Fuel cost*	6

Table 3. the system values

hour	*Le*	*Lh*	*Wind Speed*	*Solar radiation*
1	786/623	570/453	11/603	0
2	327/642	675/346	9/063	0
3	698/208	445/24	12/167	0
4	361/955	337/105	9/234	0
5	1015/51	432/551	15/088	0
6	586/828	625/725	11/01	0
7	831/909	631/993	13/953	453/463
8	672/026	638/53	13/47	817/694
9	882/365	575/465	15/426	957/05
10	658/186	609/489	10/352	454/566
11	928/608	537/985	12/064	673/964

12	990/466	682/997	11/154	611/413
13	1231/67	442/022	10/505	354/522
14	758/936	638/893	16/489	249/063
15	276/714	497/612	8/095	622/552
16	598/843	553/293	12/948	130/401
17	1143/05	649/486	11/003	143/227
18	541/16	702/186	11/119	753/55
19	1045/42	468/469	10/211	0
20	837/851	726/196	15/419	0
21	1163/42	661/121	13/214	0
22	320/727	582/229	12/114	0
23	758/049	568/428	8/588	0
24	507/505	566/002	10/164	0

The following formulae are utilized in order to calculate wind power and solar power.

Solar power is calculated as shown in Eq. (21): [9]

$$P_s = f(x) \quad (21)$$

$$= \begin{cases} (\frac{S}{S_r})P_{S-rated}, & 0 \le S \le S_r \\ P_{S-rated}, & S \ge S_r \end{cases}$$

where S is radiation intensity and S_r is radiation intensity for maximum power.

Wind power is calculated as shown in Eq. (22): [9]

$$P^w(v) = \begin{cases} 0 & if\ v \le v_{in}^c\ \ or\ \ v \ge v_{out}^c \\ \frac{v - v_{in}^c}{v_{rated} - v_{in}^c} P_r^w & if\ \ v_{in}^c \le v \le v_{rated} \\ P_r^w & if\ \ v_{rated} \le v \le v_{out}^c \end{cases} \quad (22)$$

Where V_{in} is the cut-in speed and V_{out} is the cut-out wind speed. P_r^w Is the production nominal power. Equations (21) and (22) were utilized in order to calculate the values for wind power and solar power and they are presented in Table 4 .

Table 4. calculated values for wind and solar power

Hour	*Pwind*	*Ppv*
1	69/11	0
2	46/025	0
3	74/238	0
4	47/58	0
5	100	0
6	63/719	0
7	90/477	22/674
8	86/084	40/885
9	100	47/853
10	57/74	22/729
11	73/308	33/699
12	65/028	30/571
13	59/133	17/7
14	100	12/5
15	37/226	31/1
16	81/337	6/52
17	63/658	7/16
18	64/715	37/7
19	56/463	0
20	100	0
21	83/763	0
22	73/761	0
23	41/705	0
24	56/032	0

2.3. Price changes at three levels (low load, heavy load, and peak-load hours)

As shown in Fig. 4, three time periods have been considered for electrical energy prices according to time of consumption that is as follows: low load, heavy load, and peak-load hours. As the time of consumption is drawn toward heavy load and peak-load hours, the respective cost increases. Low load hours are the best time for using electrical power aiming at charging the storage and producing hydrogen by the electrolyzer.

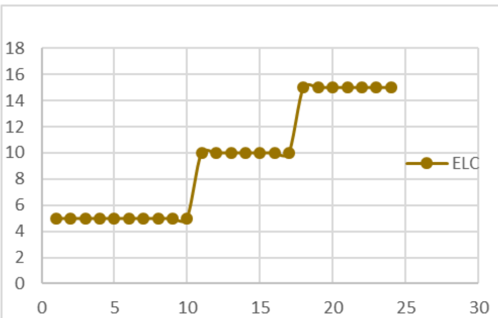

Figure 4. The Curve of Electricity Price Changes

3. Simulation Results

3.1. Emission Cost and total Cost

The amount of the produced methane depends on the amounts of the absorbed carbon dioxide, produced hydrogen, and additional surplus power to the electrolyzer. Due to the load variations, the amount of surplus power constantly changes, resulting in a change in the hydrogen produced by the electrolyzer. Accordingly, due to the low amount of stored hydrogen, the amount of produced methane and injected power should be lower. However, increasing the number of solar and wind power plants and enhancing the surplus power provide hydrogen required to exploit the maximum methane production capacity. On the other hand, this change may reduce the use of CHP, and CO2 can only be obtained from the furnace fuel, which consequently reduces the role of price change by methane produced for CHP. According to Fig. 5 using the methane reformer system results in decreasing the gas power consumption from the network and reduction of CHP production cost at the average amount of **9.08** percent In addition, considering Fig. 6 , deformation of the carbon dioxide from polluting to methane fuel has resulted in a reduction of Total Cost at the amount of **13.57** percent.

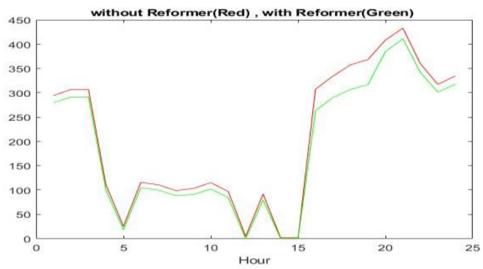

Fig. 5: CHP gas power consumption from gas network

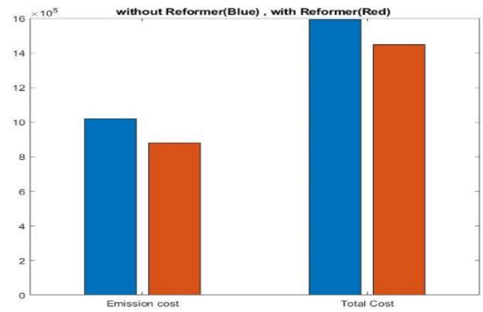

Figure 6: Emission Cost and total Cost Diagram

3.2. Load demand response

By taking advantage of the Figure and conducting calculations considering the maximized use of renewable resources as a priority, the electrical charge required in energy integrated system can be achieved as given in Fig 7:

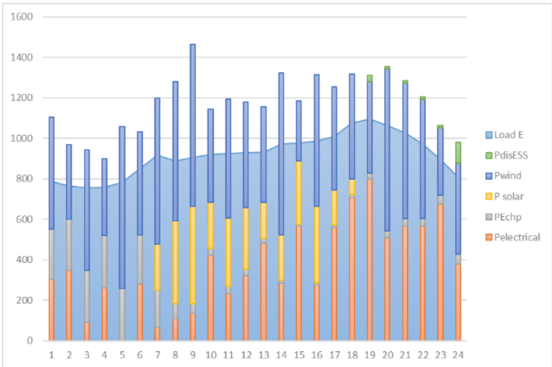

Fig 7: Hub electrical demand response

After conducting calculations by considering the maximized use of renewable resources as a priority, providing electrical power of electrolyzer for hydrogen production via electric force, and CO2 absorption from combined heat and power production systems and heat furnace, the thermal load required in energy integrated system can be achieved as given in Fig. 8:

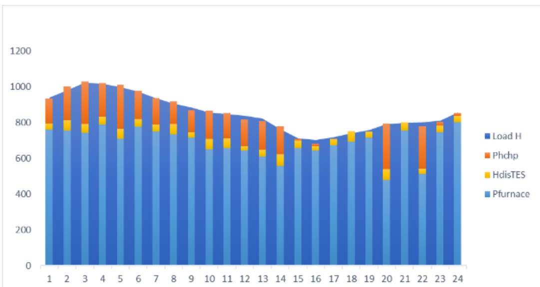

Fig. 8. Hub thermal demand response

3.3. Off-grid performance

Another feature of an energy hub is that it can function without relying on an electrical grid. As can be seen from Fig. 9, in case of a power grid outage, the proposed energy hub can provide its needed power due to owning renewable energies and existing generation capacities. As said earlier, renewable resources are uncertain, and using CHP becomes more visible alongside these resources. In such a case, the level of CO^2 absorption by the reformer increases in the production of electric power, and the increased capacity along with planning the increase hydrogen use by the reformer increase methane production. Hence, the influence of the reformer in reducing the costs will be highly significant.

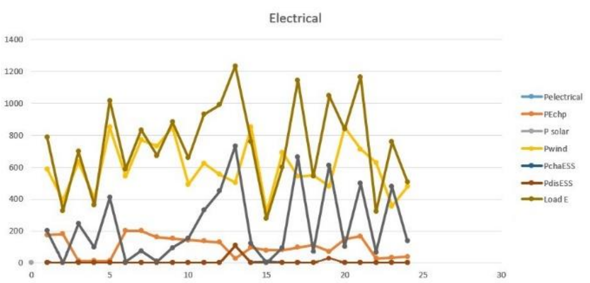

Fig. 9: Off-grid performance

3.4. Review of grid zero pollution

If the pollution level reaches zero in the energy integrated system with the aid of renewable resources, it will be called the "Zero Pollution Effect". To achieve such an objective, the total cost of pollution charge and negative cost of produced energy from renewable energies should be equal to zero. In such a case, the total cost of pollution is equal to zero that is also known as "grid zero pollution".

The level of zero grid pollution is different at each hour and is determined according to the cost of pollution at that hour. Zero grid pollution can be directly used in order to reduce system costs or reduce the total cost of pollution to reach zero by selling the excess electricity locally or to the grid. In fact, such condition has been considered for the economic performance of the system whose function is to reduce the cost of pollution to reach zero or to supply substitute thermal load in the grid with the aid of solar heat furnace, etc. This way, the level of resulting pollution in the grid reaches zero and this action needs its own conditions. Here, the cost problem has been investigated.

Condition:

$$\left(\alpha + \beta P_g(t) + \gamma P_g^2(t) + \alpha + \beta P_{gazolin}(t) + \gamma P_{gazolin}^2(t)\right) + NZE = 0 \quad (23)$$

3.5. The impact of equations on changes in gas consumption

As can be seen from the Fig. 10, using solar power stations is not possible in the initial hours of the day. Also, increasing the number of solar power stations will not influence the reduction of gas consumption levels. However, as we reach the middle of the day (noon), the level of production by solar power stations increases gradually and the level of gas consumption decreases. Such a trend will not change until nightfall and the use of solar power stations decreases after that. Ultimately, as the solar radiation decreases, the level of energy production reaches zero.

Based on the above findings, the extent of carriers' use with the potential to pollute can be reduced with the aid of grid zero pollution condition and this not only helps reduce the costs but also reduce the pollution.

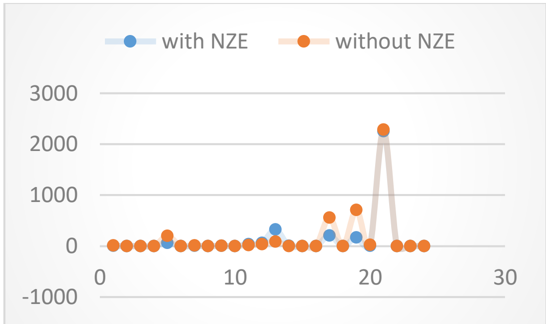

Fig. 10: The comparison before and after NZE

4. Conclusion

This article introduces a novel energy integrated system that is capable of absorbing a huge part of the CO2 produced at the outlet of combined heat and power systems and outlet of heat furnace with fuel oil and transforming it to methane needed by CHP. Also, it was observed that such action will reduce pollution by 9.06% and the total cost of the system by 13.57%. The priority of this smart management system is to use renewable resources. Also, the existing sources for saving electric energy in the system can be charged during low-load hours and pick-load hours, the energy required by the consumers can be supplied and a part of the energy required for electrolyzer can be supplied to produce hydrogen.

As mentioned in the “Review of Findings” section, the smart management system of energy hub was able to achieve the optimal extent of using one of the energy carriers aiming at minimizing the pollution, according to the extent of consumption per hour and the amount of hydrogen and methane sources in the storages during prior hours. Also, it is found that the smart energy management system has a direct impact on the extent of gas carrier usage taken from the gas network. It was demonstrated that this model was capable of reducing the extent of gas consumption by the system to a suitable level. In the “Off-grid” part, this system was able to reduce most part of the needs for sensitive loads by supplying a part of methane required by the combined power system and using distributed energy resources (DER). As mentioned in this article, the energy integrated system was able to optimize all the parameters and reduce pollution by energy carriers to a significant level.

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