This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSTE.2016.2547911, IEEE Transactions on Sustainable Energy

Considering carbon capture and storage in electricity generation expansion planning

H. Saboori and R. Hemmati

***Abstract*--Nowadays, CO2 is the primary greenhouse gas pollutant and fossil fuel-fired electrical power plants are the major producer of CO2. In this regard, it is required to equip the electrical power plants with carbon capture and storage (CCS) systems. CCS system can capture about 90 percent of the emitted carbon and significantly decreases the environmental pollutions. On the other hand, implementation of CCS increases the capital cost of the electrical power plants. As a result, the investors (or planners) in electricity generation sector should decide on constructing fossil fuel-fired units with CCS, or installing the units without pollutions such as nuclear and renewable units. But, due to growing demand for energy in the world, limitations of the renewable energy resources, and hazards of the nuclear energy, the consumption of fossil fuels is expected to growth through 2035. Regarding these issues, the investors should decide on a combination of nuclear and renewable energy power plants as well as fossil fuel-fired units equipped with CCS. This combined planning may be carried out to minimize the investment cost and the pollutions at the same time, while it satisfies the growing energy demand over the future years. The proposed decision making system is mathematically expressed through electricity generation expansion planning (GEP) problem. This paper addresses a multistage GEP including nuclear units, renewable energy units, and different fossil fuel-fired units equipped with CCS. The proposed GEP minimizes the planning costs and CO2 at the same time, while it considers CCS cost and revenue. The problem is mathematically expressed as a constrained, mixed-integer, and nonlinear optimization problem and solved using particle swarm optimization (PSO) algorithm. The problem is scheduled considering all practical constraints including security constraints of the network, and the generating units constraints of operation. Simulation results demonstrate that utilizing CCS significantly impacts on the planning output. Eventually, a comprehensive sensitivity analysis is carried out based on the CCS cost and revenue.**

***Index Terms*-- Carbon Capture and Storage; Environmental Pollution; Generation Expansion Planning; Particle Swarm Optimization; Reliability.**

I. NOMENCLATURE

Symbols, indexes and parameters

Of_1	Investment and operational costs of the existing and new generating units over the planning horizon ($)
T	Number of the stages in the planning horizon
t	t^{th} stage of the planning horizon
d	Discount rate
M, j	Number and type of the candidate technologies
$Cinv_t^j$	Investment cost for technology j at stage t ($)
X_t^j	installed candidate units at stage t
CG_t^j	Capacity of candidate technology j at stage t (MW)
Cop_t^j	Operational cost for technology j at stage t ($/MWh)
dt_t	Time duration of the t^{th} stage (hours)
α_t^j	Capacity factor (%)
X_0^j	Integer vector showing the existing units
EG_t^j	Capacity of exiting technology j at stage t (MW)
Of_2	CCS cost over the planning horizon ($)
Cp_t^j	CCS cost for technology j at stage t ($/tons)
PX_t^j	Carbon emissions of technology j at stage t (tone/kWh)
Of_3	CCS revenue over the planning horizon ($)
Rp_t^j	CCS revenue for technology j at stage t ($/tons)
Of	Total planning cost ($)
RM_t	Reserve margin of the system
RM_t^{min}	Minimum permitted reserve margin (%)
RM_t^{max}	Maximum permitted reserve margin (%)
$LOLE^{max}$	Maximum permitted LOLE (h/year)
CIT_t	Maximum permitted level for technology j at stage t
MIC_t	Maximum permitted level for all technologies at stage t
CC_t	Total installed capacity until stage t
LCI_t	Maximum permitted level for the planning cost

Abbreviations

CCGT	Combined Cycle Gas Turbines
CCS	Carbon Capture and Storage
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
ESS	Energy Storage System
FOR	Forced Outage Ratio
GEP	Generation Expansion Planning
IC Engine	Internal Combustion Engine
IGCC	Integrated Gasification Combined Cycle
LOLE	Loss of Load Expectation
NGCC	Natural Gas Combined Cycle
Oil CT	Oil Combustion Turbine
PC	Pulverized Coal
PSO	Particle Swarm Optimization

II. INTRODUCTION

There are six common air pollutants in the environment including particle pollution, ground-level ozone, carbon, sulfur oxides, nitrogen oxides, and lead. These environmental pollutants can harm the human health and also the nature. Therefore, it is required to conduct suitable investigations concerning sources of the pollutants, why they are of concern, health and environmental impacts, and how to reduce them.

The sources of the introduced air pollutants can be defined as follows; Particulate matter is a combination of very small particles and liquid droplets containing acids, organic chemicals, metals, and soil or dust particles. Ground-level ozone is mainly created by chemical reactions between NOx and VOC in the presence of sunlight. Some of the main sources

H. Saboori is with Department of Electrical Engineering, Kermanshah University of Technology, Kermanshah, Iran (e-mail: h.saboori@kut.ac.ir).
R. Hemmati is with Department of Electrical Engineering, Kermanshah University of Technology, Kermanshah, Iran (e-mail: r.hemmati@kut.ac.ir).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSTE.2016.2547911, IEEE Transactions on Sustainable Energy

of NOx and VOC can be denoted as emissions from industrial factories and electrical power plants, motor vehicle exhaust, and gasoline vapors. Carbon in different forms, e.g. CO and CO2, is mainly emitted from combustion processes such as electrical power plants. The largest sources of SO2 emissions are fossil fuel combustion in electrical power plants. The sources of NOx emissions can be stated as the emissions from cars, electrical power plants, and off-road equipment. Finally, the main sources of lead emissions are on-road motor vehicles (such as cars and trucks) and industrial sources [1, 2].

It is worth mentioning that fossil fuel-fired electrical power plants are the major source of CO2 which is the primary greenhouse gas pollutant. CO2 is accounted for approximately 75% of world greenhouse gas emissions. Regarding the aforementioned issues, fossil fuel-fired electrical power plants should be equipped with carbon capture and storage (CCS) technologies to decrease the amount of the emitted carbon. In recent years, CCS has been widely investigated regarding different aspects including capturing methods and technologies, transportation approaches, and storage methods [3, 4].

From the standpoint of the investors in electric power sector, there are two options to decrease the environmental pollutions; firs option is to invest on fossil fuel-fired electrical power plants and then employing CCS technologies to reduce the environmental pollutions, and the second option is to invest on the electrical power plants which do not emit pollutions such as nuclear, and renewable (e.g. solar and wind) power plants [5]. Therefore, the investors (or planners) should make a decision on the technologies of the new electrical power plants subject to several constraints such as limitations of the renewable energies, cost of CCS, demand for energy, pollutions, and etc. The proposed decision making system is mainly expressed as a mathematical optimization problem namely, generation expansion planning (GEP).

The electricity generation expansion planning (GEP) denotes the time, the location, the capacity and the technology of new generating units which should be constructed to meet the growing energy demand within the given security criteria over a planning horizon time of typically 10-30 years. The GEP is mathematically modeled as a constrained, mixed-integer, and nonlinear optimization problem which aims at minimizing the objective function subject to the given constraints. This optimization problem is mainly solved using the mathematical methods or Meta-heuristic optimization techniques. The mathematical methods such as dynamic programming [6], mixed integer programming [7], and linear programming [8] have been successfully applied to solve GEP. In addition, the Meta-heuristic optimization techniques such as ant colony [9], tabu search [9], genetic algorithms [10], honey bee algorithm [11], and PSO [12] have been used to solve GEP.

The GEP has also been studied considering several objective functions such as minimizing the planning cost [13], maximizing the generation company profit in deregulated electricity market [14], maximizing the reliability [10], and minimizing the environmental pollutions [15]. As well, The GEP has been investigated subject to the various constraints such as reliability [16], environmental pollutions [17], investment cost [18] and the security constraints [12].

It is worth remarking that GEP considering CCS technologies has not been investigated up to now. In this regard, this paper presents a multistage GEP considering several technologies such as nuclear, renewable, gas-fired and coal-fired types, for power plants. In addition, CCS technologies are included to capture the emitted carbon from the power plants. The operation and investment costs of the generating units, CCS cost, and CCS revenue are considered in the planning. The proposed GEP problem is expressed as a mathematical optimization programming and solved using PSO. Simulation results demonstrate that the pollutions are significantly reduced by CCS utilization and nuclear-renewable units installation as two options of investor to reduce the environmental pollution. The planning utilizes these two options at the same time to minimize the pollutions and this coordinated utilization is economically efficient.

III. Carbon emissions and EPA proposal

Electricity generation in electrical power plants is responsible for about 40 percent of U.S. emissions of CO2, which is the primary greenhouse gas. Fig. 1 shows the pollution sources in U.S. It is clear that coal and natural gas are responsible for nearly all CO2 emissions in electric power sector. It is worth remarking that over two-thirds of U.S. electricity generation uses coal and natural gas as fuel. Fig. 2 also shows that 30 percent of U.S. electricity is obtained from natural gas. In addition, natural gas is accounted for over 90 percent of new fossil generation capacity, for the next few years as shown in Fig. 3 [1, 2].

In order to tackle such pollutions, On Sept. 20, 2013, the Environmental Protection Agency (EPA) of U.S. issued a new proposal for the emitted carbon pollution from new power plants. EPA has proposed a separate standard of performance for fossil fuel-fired electric power plants as well as for CCGT units that burn coal, petroleum coke and other fossil fuels. EPA has also proposed standards for natural gas-fired stationary combustion turbines. Based on the EPA proposal, the best system of emission reduction in fossil fuel-fired units is to implement CCS. On the other hand, application of modern and efficient natural gas combined cycle technology is defined as the best system of emission reduction in the natural gas-fired units [2].

With respect to the EPA standard, large scale (100 MW or larger) and small scale natural gas-fired electrical power plants could emit no more than 1000 and 1100 pounds of CO2 per MWh, respectively. This issue is achievable through application of the latest combined cycle technology. Based on this standard, the coal-fired electric power plants have two options. In the first option, coal-fired units should begin using CCS shortly after startup to attain a 12-month average emission rate of 1100 pounds of CO2 per MWh. Otherwise; coal-fired units can begin using CCS within seven years of startup to attain a seven-year average emission rate of between 1000 and 1050 pounds of CO2 per MWh.

Based on the aforementioned proposal, the coal-fired electrical power plants should reduce their CO2 emissions through implementation of CCS. By employing CCS, they would likely not be subject to the proposed EPA standard. As well, due to

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growing demand for energy in the world, the consumption of fossil fuels is expected to grow through 2035, leading to greater CO2 emissions. Therefore, application of CCS seems to be necessary and inevitable. It is worth remarking that CCS offers the opportunity to reduce the environmental pollutions while maintaining a role for fossil fuels in national energy portfolios.

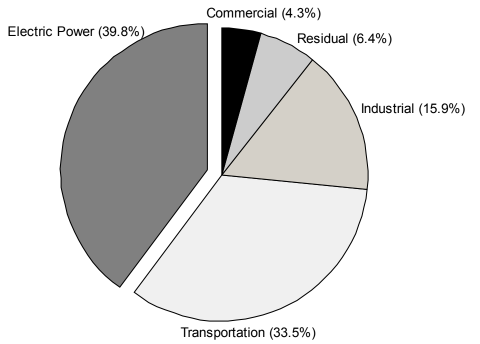

Fig. 1: 2013 U.S. CO2 Emissions

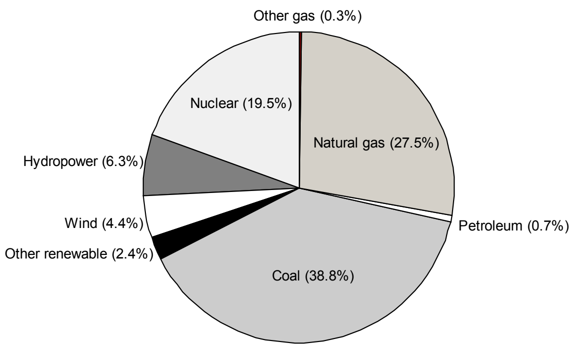

Fig. 2: 2012 U.S. Electricity Generation

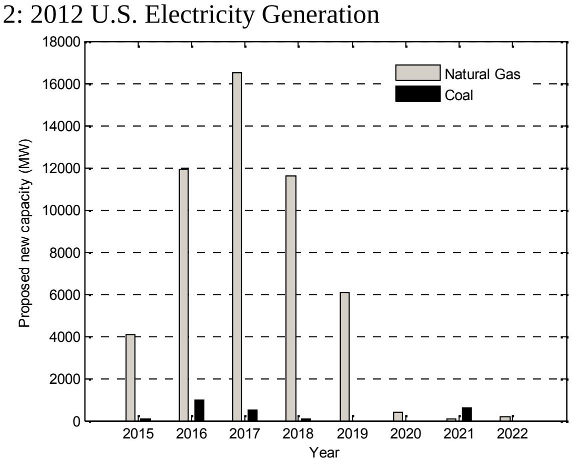

Fig. 3: Proposed U.S. Fossil Generation Capacity

IV. Carbon Capture and Storage

Carbon capture and storage (CCS) can capture up to 90 percent of CO2 emissions from an electrical power plant and store it in underground geologic formations. CCS employs the modern and efficient technologies to capture CO2 emitted by fossil fuel combustion, transport it to an appropriate storage site, and eventually store CO2 where it cannot go into the air and thus contribute to climate change. Basically, the saline formations and depleted oil reservoirs are considered as CO2 geologic storage options. In addition, the captured CO2 can be utilized in enhanced oil recovery (EOR). In recent years, CCS has been successfully implemented in many industrial application such as hydrogen production facilities, natural gas processing, and fertilizer production. Boundary Dam in Saskatchewan is the first commercial-scale coal-fired electrical power plant equipped with CCS.

A. CO2 capture

There are three main approaches for CO2 capture from the electrical power plants. Pre-combustion carbon capture is the first method. In this approach, fossil fuel is gasified (before combusted) to produce a synthesis gas, or syngas. This synthesis gas is a mixture of CO and hydrogen. Afterward, CO is converted to CO2 by a shift reaction, and then a physical solvent separates the carbon monoxide from hydrogen. For electrical power generation, pre-combustion carbon capture method can be combined with an IGCC unit that burns the hydrogen in a combustion turbine and uses the exhaust heat in the steam turbine. The second method for CO2 capture is known as post-combustion carbon capture. In this approach, the chemical solvents are mainly applied to separate CO2 out of the flue gas from fossil fuel combustion. Because of the more concentrated CO2, pre-combustion capture usually is more efficient but it also increases the capital costs of the power plant. The retrofitting of the existing electrical power plants for CO2 capture is likely to use this technique. Eventually, the third method for CO2 capture is the Oxyfuel carbon capture. In this method, the fossil fuel combustion is performed in pure oxygen. This combustion provides CO2-rich, which can be easily captured

B. CO2 transportation

The best option for CO2 transport to a storage site is the pipelines. The commercial-scale of pipelines implementation to transport CO2 has been performed in the United States at 2009. Where, 3900 miles of pipelines for transporting CO2 have been implemented for use in enhanced oil recovery [1].

C. CO2 storage

There are several options for CO2 geologic storage. Deep saline formations are one of the best places to store CO2. Deep saline formations can be found in many places and they have the largest potential for geologic storage of CO2. But their storage potential is less known because deep saline formations have not been analyzed as extensively as oil and gas reservoirs. Oil and gas reservoirs are the other option for CO2 geologic storage. This method offers geologic storage potential for CO2 as well as economic opportunity through CO2-EOR. In CO2-EOR approach, CO2 is injected into oil wells to extract the oil remaining after primary production approaches. Oil and gas reservoirs are supposed to be appropriate candidates for CO2 storage, since they have stored oil and gas resources for millions of years. Therefore, they can ensure permanent CO2 geologic storage. Finally, the un-mined coal beds can be regarded as the next option for CO2 storage. The coal beds which are too deep or too thin to be economically mined could offer CO2 storage potential. Furthermore, the captured CO2 can also be used in improved coal-bed methane recovery to obtain methane gas. It is worth remarking that basalt sites, shale basins and sub-seabed geological formations [19] are also

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accounted as the potential geologic storage locations for future [1].

D. Costs of CCS

The implementation of CCS technology increases the operational and investment costs for electrical power plants. CCS increases the costs by requiring capital investment in CCS equipment and also by consuming the electricity. CCS equipment consumes about 30% of the electricity produced by power plant and therefore reduces the net power output [1]. It has been estimated that CCS technologies would add around 80% to the cost of electricity for a new pulverized coal plant, and around 35% to the cost of electricity for a new advanced gasification-based plant. Table 1 demonstrates the levelized costs of electricity for several power plant with and without CCS. It is clear that implementation of CCS technology significantly increases the costs. Furthermore, the transportation and storage costs should also be accounted. The EPA estimates that the long-term average cost for CO2 transportation and storage is approximately \$15 per metric ton of CO2 [1, 2].

TABLE I

Levelized cost of power plants with and without CCS

Power plant type	Average levelized cost without CCS (\$/MWh)	Average levelized cost with CCS (\$/MWh)
IGCC	97.8	141.7
PC	75.0	137.1
NGCC	74.7	108.9

E. Revenues from CCS

Selling captured CO2 as a commodity can be regarded as one option to obtain revenue from CCS. In this regard, the EOR is a suitable potential for utilizing captured CO2. In addition, tax credits for capturing carbon and reducing the environmental pollutions can be considered as the other revenue from CCS. For instance in U.S., the tax credits are considered for carbon capture. In this regard, tax credits provide \$10 per metric ton of CO2 stored through EOR and \$20 per metric ton of CO2 stored through deep saline formations. It is clear that CCS revenue can compensate some part of CCS cost and reduce the CCS utilization cost.

V. MATHEMATICAL EXPRESSION OF THE PROBLEM

The mathematical expression of the proposed GEP considering CCS is given as follows;

A. Investment and operational costs of the existing and new generating units

The investment and operational costs of the existing and new generating units are presented by (1). It should be remarked that X_t^j is one of the design variables of the problem.

$$of_1 = \sum_{t=1}^{T}\left((1+d)^{-t}\left[\sum_{j=1}^{M}\left(\begin{array}{l}\left(Cinv_t^j.X_t^j\right)+\left(Cop_t^j.dt_t.(\sum_{t=1}^{t}X_t^j).CG_t^j\right)\cdot\alpha_t^j+\\ \left(Cop_t^j.dt_t.X_0^j.EG_t^j\right)\cdot\alpha_t^j\end{array}\right)\right]\right) \quad (1)$$

B. CCS costs

CCS cost of the generating units is given by (2).

$$of_2 = \sum_{t=1}^{T}\left((1+d)^{-t}\left[\sum_{j=1}^{M}\left(Cp_t^j.\left(\sum_{t=1}^{t}X_t^j\right).\left(\mathrm{CG}_t^j+\mathrm{EG}_t^j\right)PX_t^j.dt_t\right)\cdot\alpha_t^j\right]\right) \quad (2)$$

C. CCS revenue

CCS revenue of the generating units is given by (3).

$$of_3 = \sum_{t=1}^{T}\left((1+d)^{-t}\left[\sum_{j=1}^{M}\left(Rp_t^j.\left(\sum_{t=1}^{t}X_t^j\right).\left(\mathrm{CG}_t^j+\mathrm{EG}_t^j\right)PX_t^j.dt_t\right)\cdot\alpha_t^j\right]\right) \quad (3)$$

D. Final objective function

Regarding functions (1)-(3), the final objective function of the proposed GEP including CCS is given as (4). The objective function (4) is proposed to minimize simultaneously multiple objectives, such as investment and operational costs of the generating units, and also the cost of CCS over a long term planning horizon. It is worth remarking that of_1 and of_2 show the costs, while of_3 indicates the revenue and is included as a negative term.

$$\text{Min } of=of_1+of_2-of_3 \quad (4)$$

E. Security constraints of the system

The security constraints of the network are mainly presented in terms of the reserve margin and reliability. These constraints are given through (5) and (6), respectively. It should be mentioned that all existing and new installed power plants (if they are installed) are included to calculate the security constraints of the network at each stage.

$$\mathrm{RM}_t^{\min} \le \mathrm{RM}_t \le \mathrm{RM}_t^{\max} \quad \forall t \in T \quad (5)$$

$$\mathrm{LOLE}_t \le \mathrm{LOLE}^{\max} \quad \forall t \in T \quad (6)$$

F. Generating units constraints of performance

The constraints related to the generating units are given through (7) to (10). The upper bounds established for each installed technology, and the whole installed capacity at each stage are denoted by (7) and (8), respectively. Constraint (9) specifies that the total capacity of the generating units at each stage is a cumulative value. Financial limitation is also signified by (10).

$$X_t^j \le CIT_t \quad \forall t \in T \quad (7)$$

$$\sum_{j=1}^{M} X_t^j \le MIC_t \quad \forall t \in T \quad (8)$$

$$CC_t = CC_{t-1} + \sum_{j=1}^{M} X_t^j \quad \forall t \in T \quad (9)$$

$$\sum_{j=1}^{M} X_t^j.Cinv_t^j \le LCI_t \quad \forall t \in T \quad (10)$$

It should be noted that the proposed optimization problem can be solved by mathematical methods or Meta-heuristic optimization techniques. Both the mathematical and optimization approaches have already been successfully carried out to solve such problem. Both methods comprise several advantages and disadvantages. For instance, mathematical methods are accurate and their convergence is good. But, these methods require a problematic modelling specially in large-scale power systems. On the other hand, optimization techniques do not need a problematic modelling and they can easily solve large-scale power systems. But, their response is not very accurate as well as possibility of the divergence is higher. Regarding, the above issues, this paper applies modified PSO as a Meta-heuristic optimization techniques to solve the problem.

VI. The Proposed Method to Solve GEP

In this paper, the proposed mathematical optimization problem is solved using PSO algorithm. It is worth remarking that, several Meta-heuristic optimization techniques are tested to solve the problem and each algorithm is also simulated several times to proves that the obtained result is the optimum solution of the problem. However, among the applied methods, PSO finds the optimal solution sooner. As a result, PSO is chosen as the final technique in the paper. In the proposed PSO, weighing factor is linearly decreased from one toward zero as well as a mutation rate is included. As a result, this algorithm is known as modified adaptive PSO. Fig. 4 depicts the flowchart of solving the proposed problem using PSO algorithm. The blocks of this flowchart are thoroughly described in the following;

Block A: In this block, the initial population of PSO algorithm is generated based on the random procedure and the initial data of the problem are set. The PSO population is a matrix and each row of this matrix is called a particle. The elements of the particle signify number of the optimization variables (the design variables). For instance, in a problem with ten design variables, the population matrix contains ten columns (or the particle comprises ten elements).

Block B: In this section, one particle in the population is selected to be evaluated.

Block C: In this paper, each particle involves the generating units related to the all stages over the planning horizon. Therefore, in this block, the particle elements are signified and the generating units related to each stage are set on the system.

Block D: The security constraints (5) and (6) are checked in this block under all load levels and the violated constrains are denoted and saved.

Block E: The generating units constraints of performance are checked in this block. The violated constrains are denoted and saved.

Block F: This block checks the violated constrains of the problem. If there is at least one violated constraint, the current particle is removed and the next one is selected for evaluation.

Block G: Here, the objective function of the planning is calculated for the particles.

Block H: The purpose of this block is to check the program in order to evaluate all particles in the population.

Block I: In this block, the best particle in the population is selected and saved.

Block J: Here, PSO convergence criterion is checked. If convergence is reached, the optimization process is finished and the optimal solution is obtained. Otherwise, the PSO population is updated based on the following rules [20] and algorithm is reiterated.

$$v_{id}(k+1) = w(k)\cdot v_{id}(k) + c_1 \cdot rand\,(p_{best\,i,d}(k) - p_{id}(k)) + c_2 \cdot rand\,(g_{best\,d}(k) - x_{id}(k)) \quad (11)$$

$$p_{id}(k+1) = p_{id}(k) + v_{id}(k+1) \quad (12)$$

In the above equations, *rand* is a random value in the range (0, 1), parameter w shows the inertial and is linearly decreased from 0.95 to 0.2, $P_{best}(t)$ and $g_{best}(t)$ are the local and global best solutions, $p_{id}(t)$ and $v_{id}(t)$ are the population and velocity matrixes in iteration k [20].

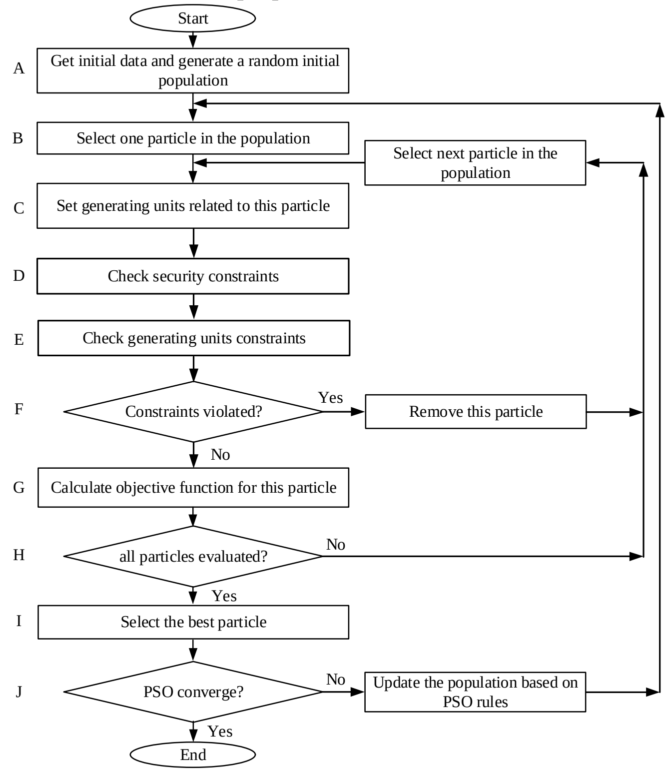

Fig. 4: Flowchart of the proposed GEP including CCS

VII. Power System Test Case

An electricity generating system including 32 exiting units and 6 candidate units for expansion is considered as case study. The characteristics of the exiting and the candidate units are listed in Tables 2 and 3, respectively [15]. The planning horizon equals 15 years and is divided into five time periods of three years each. The peak load demand is 2850 MW and annual load growth rate is 4%. The load duration curve is regarded as Table 4. Discount rate is 10%. Minimum and maximum reserve margins are 15% and 35%, respectively. CCS cost (cost of CO2 capture, transportation and storage) and also CCS revenue (tax credits and CCS-EOR) are given as Table 5 [1]. Forced outage rate of all elements is equal to 0.01.

Table II

Existing generating units and their characteristics

	N0. unit	Capacity (MW)	Var. cost ($/MWh)	Fixed OM cost ($)	CO2 (kg/MWh)
Oil/CT	2	20	18.89	2044000	1362.5
CCGT	2	20	10.95	2452000	889
CCGT	1	76	10.95	9317600	889
Coal/Steam	3	76	7.070	18635200	1840
Oil/Steam	2	100	18.89	10220000	1638
CCGT	1	100	10.95	12260000	889
Oil/Steam	3	197	18.89	20133400	1638
Oil/Steam	3	12	18.89	1226400	1638
CCGT	2	12	10.95	1471200	889
CCGT	1	155	10.95	19003000	889
Coal/Steam	3	155	7.070	38006000	1840
Nuclear	2	400	0.830	234000000	0
Oil/CT	3	50	18.89	5110000	1362.5
CCGT	3	50	10.95	6130000	889
Coal/Steam	1	350	7.070	85820000	1840

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TABLE III
Candidate generating technologies for expansion

	Capacity (MW)	Var. cost ($/MWh)	Capital cost ($)	Fixed OM cost ($)	CO2 (kg/MWh)
Oil/Steam	197	18.89	80,573,000	20,133,400	1638
Coal/Steam	155	7.07	1.79E+08	38,006,000	1840
Wind	50	0	6,9736,800	11,622,000	0
Nuclear	400	0.83	8.47E+08	2.34E+08	0
CCGT	76	10.95	40,736,000	9,317,600	889
IC Engines	12.5	26.82	11,250,000	312,500	1231

TABLE IV
Typical annual load profile and the related time durations

Load level (%)	100	90	80	70	60	50
Time duration (%)	5	20	40	60	75	100

TABLE V
CCS cost and revenue

	($/Metric ton)
CO2 cost (capture, transportation, and storage)	50
CO2 revenue (tax credits and CCS-EOR)	20

VIII. SIMULATION RESULTS

A comparative study of two cases, CCS and Non-CCS, is carried out. In Non-CCS, the CCS is not installed on the fossil-fired units, and CCS cost and revenue are not included in the planning. Table 6 demonstrates the installed capacities of the generating units at each stage over the planning horizon. Regarding the table, Non-CCS case installs different generating units to minimize the planning cost regardless of the pollution. In this case, high pollutant technologies such as coal-steam and oil-steam are installed. On the other hand, when CCS is considered in the planning, the planning installs low pollutant technologies such as wind and nuclear. Since such technologies do not need CCS, therefore the planning cost is reduced. The results illustrate that application of CCS enforces the planner to move toward the renewable and clear energies. As well, when CCS is not mandatory, the planner moves toward installing low cost power plants such as coal-fired to reduce the investment cost. Tables 7 and 8 provide a comparative study between cost and CO2 for CCS and Non-CCS cases. It is clear that through application of CCS, the total planning cost is raised up by 1.0617E+10 ($) or 64%. On the other hand, the total emitted CO2 is reduced by 6.8597E+4 (Metric ton) or 93%. The results also show that not only the total emitted CO2 is reduced, but also the emitted CO2 at each stage is considerably decreased through CCS application. These results illustrate that the network planner has to carry out a trade-off between the pollutions and the costs. In the regions or counties where the pollutions is not an important matter, planner may move toward non-CCS case and in the regions including pollution reduction regulations and policies, CCS case would be utilized. Fig. 5 demonstrates the total installed generating capacity for both cases, at each stage over the planning horizon. This figure shows that the total installed capacities for CCS and Non-CCS cases are 2373 (MW) and 2373.5 (MW), respectively. But, the installed technologies are thoroughly different as previously discussed and indicated in Table 6. Installing approximately equal capacity by two cases demonstrate that network capacity requirement is 2373 MW. But, when the pollution is not a matter, this capacity is supported through installing low cost and high pollutant power plants such as coal-fired units. On the other hand, when the pollution is important and CCS is mandatory, the network requirement is supported through high cost and low pollutant technologies such as nuclear and renewable power plants.

As it is indicated in Table 6, CCS case moves toward installing nuclear unit as the first option and wind unit as the second favorite option, while Non-CCS case installs coal-steam and oil-steam units as the first and second favorite options, respectively. Regarding this issue, total installed capacity is different for the two cases at different stages as shown in Figure 5. Because the capacities of nuclear unit (400MW) and wind unit (50MW) are significantly different from the capacities of coal-steam (155 MW) and oil-steam (197 MW) units. As well, Figure 5 shows that the fluctuations in total installed capacity by Non-CCS case is more than CCS case. For instance, the total installed capacity by Non-CCS case is suddenly increased at stage 4. While, total installed capacity by CCS case follows a uniform trend at all stages. This is due the fact that CCS case utilizes nuclear unit as the base unit and by adding wind unit, total installed capacity is slightly increased. But, Non-CCS case utilizes coal-steam unit as base power plant and by adding oil-steam unit as a high capacity unit, total installed capacity is considerably increased.

TABLE VI
Planning output for CCS and Non-CCS cases

		Oil-Steam	Coal-Steam	Wind	Nuclear	CCGT	IC Engine
Stage 1	CCS case	0	0	0	1	0	0
	Non-CCS case	0	1	1	0	1	0
Stage 2	CCS case	0	0	0	1	0	0
	Non-CCS case	1	1	0	0	1	1
Stage 3	CCS case	0	0	1	1	0	0
	Non-CCS case	1	1	1	0	1	1
Stage 4	CCS case	0	0	1	1	1	0
	Non-CCS case	1	0	0	1	1	0
Stage 5	CCS case	1	0	0	1	0	0
	Non-CCS case	1	1	1	0	1	1

TABLE VII
Planning costs for both cases

	CCS case ($)	Non-CCS case ($)
Generating Units Cost ($)	1.6337E+10	5.8412E+9
CCS Cost ($)	2.0104E+8	-
CCS Revenue ($)	8.0416E+7	-
Total Planning Cost ($)	1.6458E+10	5.8412E+9

TABLE VIII
CO2 for both cases over the planning horizon

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
CCS case (Metric ton *10E+4)	1055.7	1055.70	1055.70	1073.45	1158.25
Non-CCS case (Metric ton *10E+4)	11484.	13299.59	15115.11	16140.68	17956.21

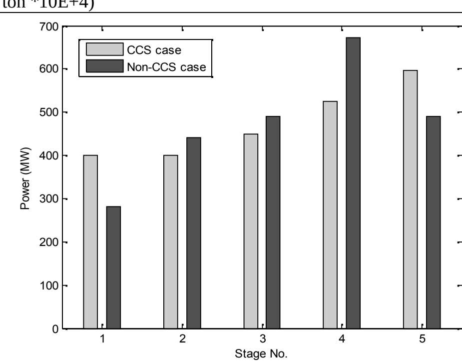

Fig. 5: Total generating capacity over the planning horizon

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSTE.2016.2547911, IEEE Transactions on Sustainable Energy

A. Evaluating the security constraints

The security constraints of the network, i.e. reserve margin and reliability, should always be satisfied. The network reserve margin is depicted in Fig. 6. It is clear that the generating capacity is placed between the minimum and maximum reserve margin levels at all stages over the planning horizon, and this constraint of performance is completely fulfilled. As well, it is not important that generation capacity curve tends asymptotically to the minimum reserve margin curve, but it is important that generation capacity curve does not violate minimum reserve margin curve and lies on it. Furthermore, the network reliability index LOLE is depicted in Fig. 7. This figure indicates that the LOLE is less than the $LOLE^{max}$ at all stages over the planning horizon and this constraint of performance is also met.

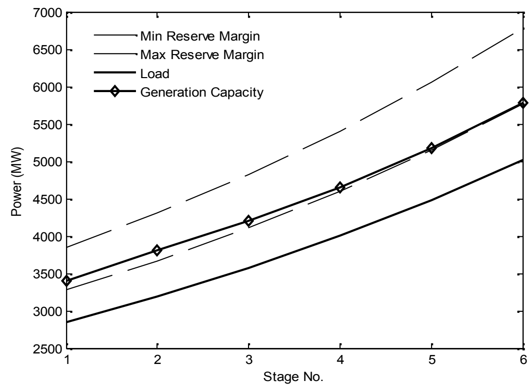

Fig. 6: reserve margin limitations over the planning horizon

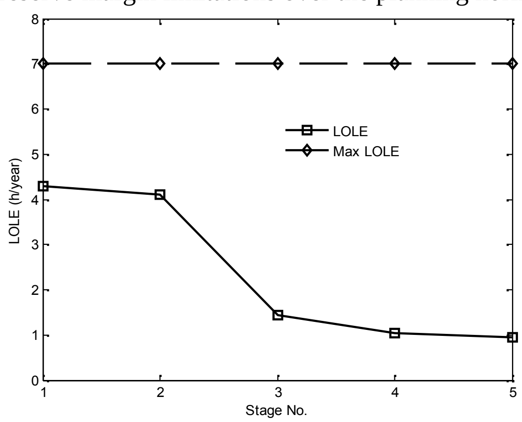

Fig. 7: LOLE over the planning horizon

B. Sensitivity analysis

A sensitivity analysis is carried out on CCS cost and revenue. Three cases are regarded as Table 9 and the results for these cases are depicted in Fig. 8. The figure demonstrates that through increasing CCS cost and decreasing CCS revenue, the planning moves toward installing low pollutant technologies such as wind. On the other hand, by decreasing CCS cost and increasing CCS revenue, the planning moves toward installing high pollutant and low cost technologies such as coal-fired and oil-fired units. The results illustrate that application of CCS can reduce the emitted CO2 through two capturing the emitted CO2 of the exiting fossil-fired and gas-fired power plants or changing the planning toward installing low pollutant technologies such as nuclear and wind units. It is also worth mentioning that most of the data in this paper are taken very close to the local data in Iran excepting those which are not available in Iran such as CCS cost. However, in order to investigate the impacts of input data on the planning, a sensitivity analysis is carried out based on the some input data as listed in Table 10. It is clear when cost or CO2 emission is increased, planning cost is also increased. As well, when reserve margin limitations are decreased, planning cost is reduced. These issues demonstrate that the proposed planning correctly includes the input data in the planning.

TABLE IX

Different CCS costs and revenues for sensitivity analysis

	CCS Cost ($)	CCS Revenue ($)
Case 1	40	30
Case 2	50	20
Case 3	60	10

TABLE X

Sensitivity analysis on the input data to the problem

Case specifications	Total Planning Cost ($)
Nominal case	1.6458E+10
Increasing reserve margin limitations by 10%	1.8225E+10
Decreasing reserve margin limitations by 10%	1.5279E+10
Increasing CO2 emission by 10%	1.6470E+10
Decreasing CO2 emission by 10%	1.6445E+10
Increasing operational cost by 5%	1.6464E+10
Increasing investment cost by 5%	1.6589E+10

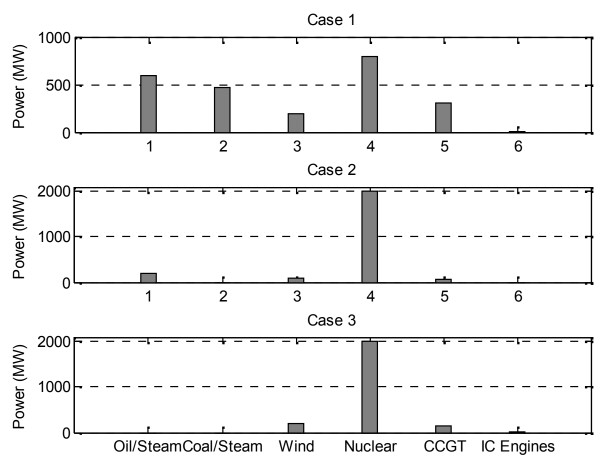

Fig. 8: Planning output under different CCS costs and revenues

IX. Conclusions

This paper introduces a mathematical model to compromise between pollutions and costs in GEP. The proposed model is expressed as a typical GEP problem and solved using PSO. The proposed GEP minimizes the planning costs and CO2 at the same time, while it considers CCS cost and revenue. All practical constraints such as security constraints of the network, and the generating units constraints of performance are included in the planning. The results demonstrate that application of CCS decreases CO2 by 93% as well as increases the planning cost by 64%. Considering CCS in the planning leads to installing low pollutant technologies and reducing the pollution. When CCS is not considered in the planning, the planning installs high pollutant and low cost technologies such as coal-steam and oil steam to minimize the planning cost regardless of the pollution. The network planner should compromise between pollution and the cost, and the proposed model is useful to carry out such a trade-off.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSTE.2016.2547911, IEEE Transactions on Sustainable Energy

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XI. BIOGRAPHIES

Reza Hemmati received the Ph.D. degree in electrical engineering from Isfahan University, Isfahan, Iran, in 2013. Presently, he is assistant professor at Kermanshah University of Technology, Kermanshah, Iran. His research interests include power systems planning, operation, and control.

Hedayat Saboori received the M.S. degree in electrical engineering from Science and Technology University, Tehran, Iran, in 2008. Presently, he works as project researcher and lecturer at Kermanshah University of Technology, Kermanshah, Iran. His research interests include power systems planning, operation, and control.