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Original Article

Multi-objective and multi-criteria optimization for power generation expansion planning with CO_2 mitigation in Thailand

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Abstract

In power generation expansion planning, electric utilities have encountered the major challenge of environmental awareness whilst being concerned with budgetary burdens. The approach for selecting generating technologies should depend on economic and environmental constraint as well as externalities. Thus, the multi-objective optimization becomes a more attractive approach. This paper presents a hybrid framework of multi-objective optimization and multi-criteria decision making to solve power generation expansion planning problems in Thailand. In this paper, CO_2 emissions and external cost are modeled as a multi-objective optimization problem. Then the analytic hierarchy process is utilized to determine the compromised solution. For carbon capture and storage technology, CO_2 emissions can be mitigated by 74.7% from the least cost plan and leads to the reduction of the external cost of around 500 billion US dollars over the planning horizon. Results indicate that the proposed approach provides optimum cost-related CO_2 mitigation plan as well as external cost.

Keywords: power generation expansion planning (PGEP), multi-objective genetic algorithm (MOGA), analytic hierarchy process (AHP), pareto optimality

1. Introduction

Electricity is one of the most requisite energy forms for socio-economic development. Economic and population growth, evolution of social lifestyle and progress of technology generally cause an increment in electricity demand. Power generation expansion planning (PGEP) plays an important role in a national power system in determination of generation technologies, timing of investments and optimal mixing pattern of different energy supplies over a long-term planning horizon which is about 15 to 30 years. PGEP can be mathematically defined as a large-scale combinatorial dynamic optimization problem with several constraints. A wide range of single objective optimization techniques is traditionally utilized to solve such a PGEP problem in terms of minimum cost approach (Santisirisomboon *et al.*, 2003; Sirikum *et al.*, 2007; Nakawiro *et al.*, 2008). However, since electricity production results in environmental impacts, least cost modeling can no longer be appropriate. For solving the modern PGEP, multi-objective optimization models therefore become much more attractive (Antunes *et al.*, 2004; Murugan *et al.*, 2009).

The genetic algorithm (GA) is a robust stochastic search method based on the concept of the fittest survival. Applying GA to solve PGEP problems has a long and successful history (Kannan et al, 2005; Sirikum, 2007; Pereira and Saraiva, 2010). Being an evolutionary-based approach, GA can be flexibly modified for solving multi-objective optimization problems. In this study, a multi-objective genetic algorithm (MOGA) is applied and employed based on a merit of non-dominated sorting genetic algorithm version II (NSGA-II) with elitism preserving as well as non-parameter crowding approach (Deb et al., 2002).

There are two general approaches to multi-objective optimization. The first approach, based on a prior knowledge

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of all necessary criteria, can interpret the multi-objective optimization problem as a single objective by linear combination of all original criteria, which is called the "a priori approach". Nevertheless, with improper selection of weights in all objectives, the obtained single solution may not be the most advisable one. Moreover, when these objectives are in conflict with each other, one solution can improve one objective and deteriorate the others at the same time. No single solution can be the best for all conflicting objectives. Instead of a single solution, the second approach, which is called the "a posterior approach", refers to a procedure of selecting the best solution from "Pareto-front", "Pareto optimal", or "non-dominated set". The set contains a trade-off solution that is not inferior to the other feasible solution in all objectives or superior to the other feasible solution in at least one objective. This approach requires an efficient decision making tool to determine the best solution with respect to all criteria or policy maker's preferences.

Multi-criteria decision making (MCDM) involves the procedure of selection of the most appropriate solution to the problem in the presence of the non-commensurate and conflicting criteria. The solution therefore must be compromised to the decision maker's preferences. This approach can be applied for identification of a set of non-dominated solutions. For synthesizing and ranking the scores of all possible alternatives with several criteria and sub-criteria of the problems, the analytic hierarchy process (AHP) (Saaty, 2008) is an effective tool which can be applied to decompose the complex problem into a hierarchical tree, which is utilized for scaling or weighting the importance of all criteria. The final decision can be made by the ranked score of all possible alternatives. Therefore, the AHP can be applied for selection of the compromised solution from Pareto frontier.

The vulnerability index of fuel import is determined by how much the payment of fuel imports affects the gross domestic product (GDP). The vulnerability, which is widely applied to indicate the security of energy resource, has been taken into account in power system planning. The general purpose of electricity production is to serve the continuous predicted demand in order to ensure the system reliability. Expected energy not served (EENS) and loss of load probability (LOLP) as common reliability indicators describe the possibility of system failure, which is expected to be as small as possible. Nevertheless, the reduction of these indicators is normally achieved by increasing the capacity so that total expansion cost is increased. There is a general acceptance that electricity production and consumption have increased environmental damages in many aspects. The negative externalities refer to any action which adversely affects other groups without direct compensation. The appraisal of environmental damage is called "the external cost" (Rafaj and Kypreos, 2007). An approach of combining an external cost into the total production cost executes an efficient policy instrument to ensure that the negative externalities of various generating technologies are evaluated in concurrence with market mechanisms. Furthermore, the issue of climate change increases critical awareness at national as well as global levels. The increasing atmospheric concentration of greenhouse gas entails higher possibility of global warming. Therefore, the mitigation of CO_2 emission and negative externalities is an important criterion in seeking new generation technologies.

In this study, the proposed hybrid framework is presented to deal with a multi-objective PGEP. Three objectives are considered: minimization of generation and expansion cost, CO_2 emission, and external cost. Two stages of framework to account for multi-objective optimization and decision making are integrated using the MOGA and AHP. Firstly, the desirable set of non-dominated solutions is approximately determined using the MOGA. Then AHP is used to rank these solutions to determine the best single solution. Four criteria, namely economic, environment, reliability and vulnerability are concerned for decision making. In this paper, simulation results are presented of various capacity expansion plans. All cases are compared to the least cost plan, a single objective optimization, in order to clarify the compromise of the solution. This study also presents the PGEP for Thailand as a model case study.

2. Mathematical Formulation of the Multi-Objective PGEP Problem

The PGEP problem can be formulated as a multi-objective model with two or more objectives. In a general multi-objective optimization, several objectives are in conflict and incommensurate to each other, and thus they must be optimized simultaneously.

In this study, three objective functions are used to minimize the generation expansion cost, CO_2 emissions and external costs. The generation expansion costs in the first objective function (Obj_{cost}) can be mathematically defined as a mixed integer linear programming (MILP) model. The problem therefore requires both continuous and integer variables. The continuous variables denote the net power output of the installed generating units, and the discrete ones relate to the capacity of the candidate units for power expansion. The desirable objective function is modified and fulfilled (Antunes *et al.*, 2004; Kannan *et al.*, 2005; Murugan *et al.*, 2009). The formulation comprises investment cost, salvage value, fixed and variable operation and maintenance (O&M) costs as well as fuel costs, by the following expression,

$$\min_{u,p} \quad Obj_{\text{cost}} = \sum_{t=1}^{T} \left[I_t - S_t + F_t + V_t \right] \tag{1}$$

The objective function to be determined I_t, S_t, F_t and V_t are as follows

$$I_t = \left(\frac{1}{1+D} \right)^{t-1} \left[\sum_{i=1}^{I} \left[Inv_i \cdot Cap_i \cdot u_{i,t} \right] \right] \tag{2}$$

$$S_t = \left(\frac{1}{1+D} \right)^{T} \sum_{i=1}^{I} \left[\delta_i^{T-t+1} \cdot Inv_i \cdot Cap_i \cdot u_{i,t} \right] \tag{3}$$

$$F_t = \left(\frac{1}{1+D}\right)^{t-\frac{1}{2}} \left(\sum_{r=1}^{t}\sum_{i=1}^{I}\left[Fixed_i \cdot Cap_i \cdot u_{i,r}\right] + \sum_{j=1}^{J}\left[Fixed_j \cdot ExistCap_j\right] \right) \tag{4}$$

$$V_t = K \cdot \left(\frac{1}{1+D}\right)^{t-\frac{1}{2}} \sum_{s=1}^{S} s \left[\sum_{i=1}^{I}\left[Var_i \cdot p_{i,s,t}\right] + \sum_{j=1}^{J}\left[Var_j \cdot p_{j,s,t}\right] \right] \tag{5}$$

where I_t denotes total investment cost, S_t denotes salvage value of candidate unit, F_t denotes fixed O&M costs and V_t denotes variable cost comprising fuel cost and variable O&M costs in the t^{th} year. The integer decision variable, $u_{i,t}$ represents the decision variable of generating unit of the i^{th} candidate technology in the t^{th} year. The continuous decision variable, $p_{i,s,t}$ represents the power output of the i^{th} candidate technology of the s^{th} subperiod in the t^{th} year and $p_{j,s,t}$ represents the power output of the j^{th} existing technology of the s^{th} subperiod in the t^{th} year. The parameters, Cap_i, Inv_i, δ_i, $Fixed_i$ and Var_i represent the capacity, investment cost, salvage value, fixed and variable operational maintenance charges of the i^{th} candidate technology, respectively. $ExistCap_j$, $Fixed_j$ and Var_j represent the capacity, fixed and variable O&M costs of the j^{th} existing technology, respectively. The constants, D and K are discount rate and number of hours in subperiod, respectively. The indices, I, J, S and T are number of candidate technologies, existing technologies, subperiods in a year and length of planning horizon, respectively.

The second objective function ($Obj_{\mathrm{CO_2}}$)is the CO$_2$ emission function associated with the energy output of power plants and emission factors,

$$\min_{p} \quad Obj_{\mathrm{CO_2}} = K \cdot \sum_{t=1}^{T}\left[\sum_{s=1}^{S} s \left[\sum_{i=1}^{I}\left[EF_i \cdot p_{i,s,t}\right] + \sum_{j=1}^{J}\left[EF_j \cdot p_{j,s,t}\right] \right]\right] \tag{6}$$

where EF_i and EF_j are the CO$_2$ emission factor of the i^{th} candidate technology and the j^{th} existing technology.

The external cost function (Obj_{Ext}) minimizes negative externalities which relate to the energy output and a coefficient of the external cost from each type of power plants,

$$\min_{p} \quad Obj_{\mathrm{Ext}} = K \cdot \sum_{t=1}^{T}\left[\sum_{s=1}^{S} s \left[\sum_{i=1}^{I}\left[Ext_i \cdot p_{i,s,t}\right] + \sum_{j=1}^{J}\left[Ext_j \cdot p_{j,s,t}\right] \right]\right] \tag{7}$$

where Ext_i and Ext_j are the external cost of the i^{th} candidate technology and the j^{th} for the existing technology.

The mathematical constraints of the MOPGEP are derived from reserve margin, electricity demands, availability and retirement of the plants. In the planning horizon, the total installed capacity in the power system must satisfy maximum and minimum reserve margins. The total installed capacity is the summation of the existing and selected candidate capacity, as well as the elimination of capacity of plant retirement. In each subperiod, Equation 8, the total power generation incorporated by all generating units must be sufficient for the forecasted electricity demand in Equation 9. Furthermore, the power generation by each existing and candidate unit must not exceed capacity in Equation 10 and 11. Renewable energy provides cleaner electricity without any fossil-fuel requirement. Nevertheless, it has the limitation of renewable resources, Equation 12. The above mentioned constraints are formulated as follow;

$$\left(1+\mathrm{R}_{\min}\right)\cdot Load_{1,t} \le \sum_{r=1}^{t}\left[\sum_{i=1}^{I}\left[Cap_i \cdot u_{i,r}\right] - \sum_{j=1}^{J}\left[Retire_{j,r}\right] \right] + \sum_{j=1}^{J} ExistCap_j \le \left(1+\mathrm{R}_{\max}\right)\cdot Load_{1,t} \tag{8}$$

$$\sum_{i=1}^{I}\left[\sum_{s=k}^{S}\left[p_{i,s,t}\right] \right] + \sum_{j=1}^{J}\left[\sum_{s=k}^{S}\left[p_{j,s,t}\right] \right] \ge Load_{k,t} \tag{9}$$

$$\sum_{s=k}^{S}\left[p_{j,s,t}\right] \le AF_j \cdot ExistCap_j - \sum_{r=1}^{t}\left[Retire_{j,r}\right] \tag{10}$$

$$\sum_{s=k}^{S}\left[p_{i,s,t}\right] \le \sum_{r=1}^{t} AF_i \cdot Cap_i \cdot u_{i,r} \tag{11}$$

$$\sum_{t=1}^{T} u_{i,t} \le PRE_i \tag{12}$$

where R$_{\min}$ and R$_{\max}$ denote the minimum and maximum reserve margin, respectively. AF_i and AF_j denote the availability factor of the i^{th} candidate technology and the j^{th} existing technology, respectively. PRE_i denotes the maximum capacity of the j^{th} renewable energy. $Load_{k,t}$ denotes load level of the k^{th} subperiod in the t^{th} year. $Retire_{j,r}$ denotes the retirement of the j^{th} existing technology in the t^{th} year.

3. Framework in MOPGEP Problems

In this study, the hybrid approach integrating multi-objective optimization and multi-criteria decision making is used to solve the MOPGEP problem based on the *a posteriori approach*. The method is therefore composed of two computing stages, where the former and latter stages are called "optimization stage" and "decision stage", respectively.

3.1 Optimization stage

Since the set of non-dominated solution is required for providing more alternatives to satisfy several goals of PGEP simultaneously, the MOGA is proposed and modified in order to curtail the computational time and to improve the optimization performance. The modified MOGA is explained as shown in Figure 1.

To begin the procedure of multi-objective optimization, the MILP method is utilized to minimize three single objective functions individually. The obtained solutions play an important role in instructing MOGA about a good starting point of non-dominated solutions over the objective space. A large scale MOPGEP problem is separated into main- and sub-program according to the corresponding types of decision variables. In order to determine which appropriate

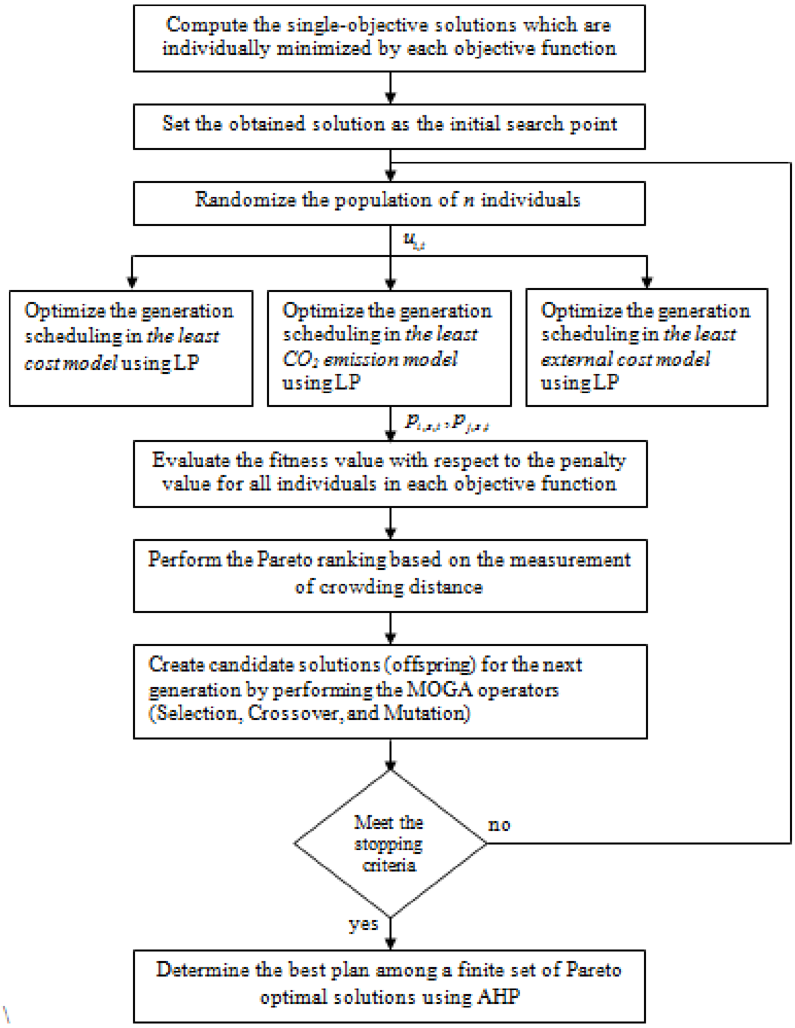

Figure 1. Overview of the framework for MOPGEP.

generating technology should be selected and how much capacity is expanded, the main-program is set to optimize the combination of candidate generating units ($u_{i,t}$), which are integer variables and are represented by chromosome in MOGA. All chromosomes in the population are randomized for initial values.

In the MOGA procedures, the sub-program is to deal with generation scheduling for seeking the sufficient and optimal power levels of installed capacity ($p_{i,s,t}$, $p_{j,s,t}$). The problem can be solved by linear programming (LP). The LP sub-program is performed for optimization of three objective functions: the least cost, CO_2 emissions, and external cost of power generation.

Then the Pareto ranking is performed (see Figure 1). The Pareto ranking approach (Konak *et al.*, 2006) involves the procedure to determine the fitness of each solution which results in the possibility of the solution to survive in the next generation. The objective values of each solution are the required information to rank the non-dominated solution of the population. In order to deal with several constraints, the penalty value is added to the objective value when the candidate solutions are infeasible. The more the solution violates the constraints, the higher the penalty value attributed to the objective value.

All solutions in the population are categorized into an ordinal Pareto front. The first Pareto front embraces non-dominated solutions which are disregarded temporarily for determining the other levels of Pareto front and this procedure is repeated until the entire population is investigated. A solution in a lower level of Pareto front is equivalent to a better one in the multi-objective manner. Each solution is penalized by the number of every other solution in the lower Pareto fronts when it is dominated.

The crowding distance approach (Konak *et al.*, 2006) has been used in NSGA-II to procure solutions spread-out uniformly throughout Pareto front. For each objective function, the solutions in each Pareto front are sorted by their objective. The maximum and minimum values are set at an infinite crowding distance value. For the entire population, the selection procedure is controlled by Pareto ranking and crowding distance. The Pareto ranking has priority over the crowding distance. When two solutions are in different ranks, the solution with higher rank is more desirable. Otherwise, when both solutions are members of the same rank, the solution with longer crowding distance is more desirable.

To adapt old solutions for better ones, as shown in Figure 1, a tournament selection approach has collected a solution with higher fitness by means of electing a number of solutions, the tournament size of players, at random from the population, and then the best fit solution to be determined as a parent. Crossover and mutation operators of GA explore and exploit structures of compromise solutions with respect to three objectives for creating new non-dominated solutions. A heuristic crossover approach produces a new solution, called a child, from the two parents. A Gaussian mutation approach changes each element of the randomized child vector with a small probability via appending a random number from a Gaussian distribution with the zero-mean and user-defined standard deviation (1.0 was set in this study). All steps are repeated until all criteria are satisfied.

3.2 Decision stage

In the next stage, a set of non-dominated solutions is analyzed to determine the most appropriate expansion plan. The AHP, one of the most flexible and powerful MCDM algorithms, has potential to identify a single solution, such as a compromised set of non-dominated solutions. Based on the hierarchical decomposition technique, the AHP requires the well-defined structure of the particular complex problem to decompose such a problem into the simple components. The top level of hierarchy must be an aggregated goal of the problem. The goal is decomposed into each criterion at the second level. The subsequent levels are further disaggregated into more unequivocal sub-criteria that contribute to the quality of alternatives. In this study, four criteria of PGEP; namely, economic, environment, reliability and vulnerability are established for the decision on power capacity expansion. The criterion of environment has two sub-criteria including the CO_2 emission and the external cost. The sub-criteria of import vulnerability are concerned about the energy supply of coal and natural gas for power generation. The expected energy not served represents the criterion of reliability. The equivalent energy function (EEF) method is employed using a recursive convolution approach to obtain the mentioned result (Wang and McDonald, 1994). The proposed hierarchy is illustrated in Figure 2.

Normally, the multi-objective optimization provides several non-dominated solutions which are referred to the term “Plan” in Figure 2 due to providing different capacity expansion and generation mix. Therefore, all obtained plans also indicate different quantities of the above-mentioned decision criteria such as generation cost, CO_2 emission, external cost, and others. AHP structure in Figure 2 is used to calculate the score of all plans and the plan with the highest score would be more attractive to the PGEP.

A pair-wise comparison technique is utilized with Saaty’s assessment scale to indicate the proportional importance between two criteria or sub-criteria (Saaty, 2008). For each branch of each level in the hierarchy, pair-wise comparisons are executed and converted into matrix form.

This reciprocal matrix manifests properties of homogeneity $\left(a_{ij} \cdot a_{ij} = 1\right)$ and reciprocity $\left(a_{ij} = 1/a_{ji}\right)$. When the matrix satisfies a property of consistency $\left(a_{ik} \cdot a_{kj} = a_{ij}\right)$, each column j^{th} of this $n \times n$ matrix can be derived from an eigenvector and its corresponding Eigenvalue n. The advantage of AHP is to provide the consistency measurement of the obtained priority via consistency ratio (CR). To ensure pair-wise comparisons, Saaty recommended that the CR should be less than or equal to 0.1. Otherwise, the decision maker should revise the criteria judgment until the CR is satisfactory.

4. Case Study Thailand

As data intensive problem, utilization of technical and statistical information in modeling must be strongly concerned with their reality. To compose the required parameter of MOPGEP model, the data have been collected and synthesized from several sources. The Electricity Generating Authority of Thailand (EGAT) and the Ministry of Energy are responsible for formulation of the Power Development Plan 2010 (PDP 2010) to elevate reliable electricity supply, and efficient power generation. The PDP methodology has employed the least cost optimization subject to reserve margin, electricity demand and national energy policy such as power imports from neighbor, nuclear power project, energy efficiency improvement, demand side management as well as renewable energy development. Various researchers have developed the PDP methodology in terms of CO_2 mitigation, energy security improvement and impact assessment of the related energy policies (Santisirisomboon *et al.*, 2003; Nakawiro *et al.*, 2008; Promjiraprawat and Limmeechokchai 2012). In this study, the planning horizon is the period between 2010 and 2030 according to PDP 2010 plan (EGAT, 2010). A discount rate of 10% per year is used to compute the

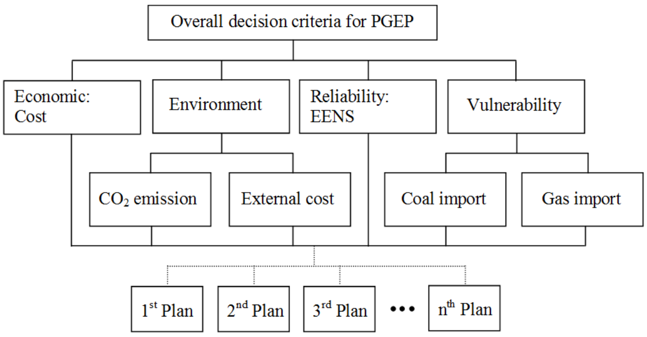

Figure 2. Proposed AHP hierarchy.

present worth of the total costs. The surplus capacity is always maintained between 15% and 25% of reserve margins to ensure system reliability. In this study, the fuel price of natural gas, coal, lignite, fuel oil, diesel, uranium and biomass is 9.76, 4.01, 0.95, 14.3, 20.51, 0.5 and 2.01 $/MMBtu, respectively (Santisirisomboon *et al.*, 2003; Nakawiro *et al.*, 2008; EGAT, 2010). The other important hypothesis and limitations in the model are in the following sections.

4.1 Thailand load forecast

In the PDP 2010 plan, the electricity consumption is forecasted to increase from 144,790 GWh in 2009 to 433,815 GWh in 2030. Load pattern is represented by the predicted load factors on an average of 74.42% per year. In this study, each year of the planning horizon is divided into 12 equal segments containing 730 hours. Load levels in each segment can be obtained from hourly load duration curves (EGAT, 2010). To obtain the load duration curve (LDC), the segments are sorted as shown in Table 1.

4.2 Existing power plants

The existing Thailand power system is composed of various generating technologies with an installed capacity of 29,212 MW (EGAT, 2010). Independent power producers (IPP) and EGAT are responsible for the system electricity production. Natural gas is the primary energy supply, and accounted for a 70% share in total fuel consumption in 2008 (DEDE, 2009). On the contrary, renewable technologies such as hydro, biomass, wind and solar energy shares are very small in total capacity. The details of technical, economic and environmental information of 13 existing power plants are available in Table 2. Furthermore, the retirement schedule is considered for replacement of existing power plants.

4.3 Candidate power plant and description of case studies

This study includes seven case studies, namely the “base case”, the “integrated gasification combined cycle (IGCC) case”, the “supercritical case”, the “biomass case”, the “carbon capture and storage (CCS) case”, the “nuclear case”, and the “renewable case”. In addition, all case studies in the multi-objective optimization are compared with the least cost plan, which is the single objective optimization.

Since the total installed capacity in Thailand is dominated by coal-fired thermal (TH-Coal), gas-fired combined cycle (CC-Gas) and diesel-fired gas turbine power plant (GT-Diesel), three different kinds of traditional fossil-based generating technologies are introduced as candidate power plants for the base case and the others.

For IGCC, biomass, nuclear and supercritical cases, the corresponding generating technology is further selected as the four candidate power plants of the corresponding cases.

Table 1. Load forecast (MW) during 2009-2030.

Year	Subperiod											
	1	2	3	4	5	6	7	8	9	10	11	12
2009	22,045	20,844	19,945	19,113	18,239	17,153	15,914	15,014	14,308	13,526	12,461	9,782
2010	23,249	21,751	20,852	20,020	19,146	18,060	16,821	15,921	15,215	14,433	13,368	10,690
2011	24,568	22,550	21,651	20,819	19,945	18,859	17,620	16,720	16,014	15,232	14,167	11,487
2012	25,913	23,389	22,490	21,658	20,784	19,698	18,459	17,559	16,853	16,071	15,006	12,324
2013	27,188	24,217	23,318	22,486	21,612	20,526	19,287	18,387	17,681	16,899	15,834	13,155
2014	28,341	25,086	24,187	23,355	22,481	21,395	20,156	19,256	18,550	17,768	16,703	14,026
2015	29,463	25,952	25,053	24,221	23,347	22,261	21,022	20,122	19,416	18,634	17,569	14,891
2016	30,754	26,929	26,030	25,198	24,324	23,238	21,999	21,099	20,393	19,611	18,546	15,868
2017	32,225	27,955	27,056	26,224	25,350	24,264	23,025	22,125	21,419	20,637	19,572	16,900
2018	33,688	29,004	28,105	27,273	26,399	25,313	24,074	23,174	22,468	21,686	20,621	17,948
2019	34,988	29,979	29,080	28,248	27,374	26,288	25,049	24,149	23,443	22,661	21,596	18,924
2020	36,336	31,022	30,123	29,291	28,417	27,331	26,092	25,192	24,486	23,704	22,639	19,964
2021	37,856	32,101	31,202	30,370	29,496	28,410	27,171	26,271	25,565	24,783	23,718	21,043
2022	39,308	33,184	32,285	31,453	30,579	29,493	28,254	27,354	26,648	25,866	24,801	22,122
2023	40,781	34,296	33,397	32,565	31,691	30,605	29,366	28,466	27,760	26,978	25,913	23,234
2024	42,236	35,448	34,549	33,717	32,843	31,757	30,518	29,618	28,912	28,130	27,065	24,392
2025	43,962	36,634	35,735	34,903	34,029	32,943	31,704	30,804	30,098	29,316	28,251	25,578
2026	45,621	37,877	36,978	36,146	35,272	34,186	32,947	32,047	31,341	30,559	29,494	26,818
2027	47,344	39,166	38,267	37,435	36,561	35,475	34,236	33,336	32,630	31,848	30,783	28,107
2028	49,039	40,511	39,612	38,780	37,906	36,820	35,581	34,681	33,975	33,193	32,128	29,455
2029	50,959	41,892	40,993	40,161	39,287	38,201	36,962	36,062	35,356	34,574	33,509	30,840
2030	52,890	43,339	42,440	41,608	40,734	39,648	38,409	37,509	36,803	36,021	34,956	32,283

Table 2. Technical, economic and environmental characteristics of power plants.

Plant code	Capital cost ($/MW)	Capacity (MW)	Hate rate (M.Btu/ MWh)	Fixed O&M ($/MW/Yr)	Variable O&M ($/MWh)	FOR (%) (kg/MWh)	AF (%) ($/MWh)	CO_2 emission factor [a]	External cost [b]
Existing power plant [c]									
TH-Coal	IPP	1,717	9,100	229,495	0.64	5.5	92	973	152.3
TH-Lignite	EGAT	2,180	9,687	38,909	1.77	5.5	92	1,159	233.5
CC-Gas	IPP	9,225	7,250	83,190	0.44	4.2	94	370	16.1
CC-Gas	EGAT	5,857	7,966	17,200	0.44	4.2	94	370	16.1
TH-Gas	IPP	1,580	10,423	62,500	0.45	5.5	92	631	41.8
TH-Gas	EGAT	2,920	10,108	20,500	0.55	7	92	631	41.8
GT-Gas	EGAT	220	13,651	9,000	0.07	2.5	96	631	26.0
TH-Oil	EGAT	324	9,289	22,000	0.58	7	92	796	87.8
DT-Diesel	EGAT	124	10,289	7,000	0.29	2.5	96	808	35.2
GT-Diesel	EGAT	610	15,456	7,000	0.29	2.5	96	808	35.2
Hydro	EGAT	3,424	-	49,500	0.13	10.1	23	23	7.3
Biomass	SPP	287	10,976	34,200	0.97	7.1	83	58	34.5
Renewable	EGAT	34	-	67,800	1.10	10.1	20	34	1.3
Candidate power plant [d]									
TH-Coal	1.05	800	9,260	38,000	0.76	6	83	973	152.3
GT-Diesel	0.43	290	10,410	58,500	0.54	2.5	83	808	35.2
CC-Gas	0.71	800	6,800	36,600	0.66	4	83	404	16.1
IGCC-Coal	1.55	500	7,346	34,200	0.93	7.1	83	766	13.4
S-Coal	1.57	800	9,125	30,600	0.79	7.1	83	782	16.0
Biomass	1.45	100	10,976	34,200	0.97	7.1	83	58	34.5
Nuclear	3.02	1,000	10,953	66,600	0.20	8	83	21	6.4
TH-Coal-CCS	1.88	800	9,125	46,800	1.61	6	83	143	13.4
IGCC-Coal-CCS	1.94	500	7,346	46,800	1.30	7.1	83	97	11.4
Wind	1.32	3	-	13,500	0.88	10.1	30	18	1.3
Solar	4.16	5	-	9,000	1.32	10.1	10	49	3.1
Small hydro	2.74	3	-	49,500	0.13	10.1	35	23	1.3

TH-Coal (Coal-fired thermal), TH-Lignite (Lignite-fired thermal), CC-Gas (Gas-fired combined cycle), GT-Gas (Gas-fired gas turbine), TH-Oil (Oil-fired thermal), DT-Diesel (Diesel turbine), GT-Diesel (Diesel-fired gas turbine), IGCC-Coal (Coal-fired integrated gasification combined cycle), SU-Coal (Coal-fired supercritical), TH-Coal-CCS (Coal-fired thermal with carbon capture storage) and IGCC-Coal-CCS (Coal-fired integrated gasification combined cycle with carbon capture storage). O&M, FOR and AF stand for operation and maintenance, forced outage rate and availability factor respectively. Data reported is derived from various sources and literature reviews. [a] adopted from Chatzimouratidis and Pilavachi (2007); IPCC (2007), Electricity Generating Authority of Thailand (EGAT) (2010), Koornneef *et al.* (2010); [b] adopted from Rafaj and Kypreos (2007), Chatzimouratidis and Pilavachi (2009), Georgakellos (2010); [c] adopted from Department of Alternative Energy Development and Efficiency (DEDE) (2009), Generating Authority of Thailand (EGAT) (2010); [d] adopted from International Energy Agency (IEA) (2005), Rafaj and Kypreos (2007), Nakawiro et al. (2008), Kannan (2009), and Pereira and Saraiva (2010).

In the biomass case, due to availability limitations, the constraint of cumulative installed capacity must not exceed 4,400 MW (EGAT, 2010) in the planning horizon. Due to the time frame of construction and public acceptance, the first nuclear power plant will be taken into account in 2020 and would be limited to two units per year at most.

In addition, TH-Coal-CCS and IGCC-Coal-CCS plants are investigated in the CCS case. Finally, the renewable case is the largest problem in this study due to related variables. Three renewable technologies, which include small hydro, wind and solar power, are introduced and their total capacity is restricted to a maximum of 1600, 700, and 50,000 MW respectively, according to the limitations of renewable potential in PDP 2010 (EGAT, 2010). The technical, economic and environmental characteristics of these candidate power plants are summarized in Table 2.

5. Simulation Results

In this study, the model was operated on Pentium quad-core processor at 2.66 GHz with 3 GB of RAM. The GAMS program provides ILOG Cplex 9.0 solver for handling efficiently MILP problems. The MATLAB R2010a language is utilized for implementation of multi-objective optimization and AHP analysis.

As shown in Figure 3, three dimensional non-dominated or Pareto optimal solutions of the seven case studies, obtained by using MOGA, demonstrate the compromise among expansion and generation costs, CO_2 emissions and the external cost. Non-dominated solutions are sensitive to the parameters setting in a meta-heuristic approach. With respect to an appropriate parameter adopted from testing in a small scale problem, MOGA was set at the population size of 1,000 for 10,000 generations with crossover and mutation probabilities of 0.8 and 0.15, respectively. The effect on the selected Pareto fraction of 0.35 limits the number of compromised plans to be 350 plans for each case study.

It is noted that each case studies provide different benefits with respect to three objectives including expansion cost, CO_2 emission and external cost. For example, the base case has provided the expansion cost of between 121 and 161 billion US dollars, CO_2 emission of between 2010 and 4,256 $MtCO_2$ and external cost of between 92 up to 638 billion US dollars. In the Figure 3, it can be seen that a plan with low expansion cost provide definitely a high CO_2 emission and external cost. On the other hand, the relationship between CO_2 emission and external cost is highly correlated in nature because generating technology with a low external cost tends to have a low CO_2 emission.

In this study, from personal interviews with experts, environmental concern is the most important criterion for establishing the environmental-friendly policy. However, the economic criterion is still necessary for preventing expensive electricity production. Based on the interviews with the experts, the assessment scale of the AHP and the corresponding matrices are shown in Table 3.

For criteria comparison, the λ_{max} is equal to 4.0488 and exhibits the acceptable CR of 0.0181. In fact, 2×2 reciprocal matrices are always consistent and is always equal to 2 for both sub-criteria comparisons. The corresponding priority vector can be interpreted as the weighed coefficient of linear combination for ranking alternatives. The expansion and generation cost is the most important criterion as its weight is 32.16% followed by CO_2 emission (31.8%), external cost (15.9%), EENS (13.25%), coal dependency (5.17%) and gas dependency (1.72%). In order to gain the compromised plan for power generation expansion, the AHP ranks alternative from Pareto fronts of each case study according to their attributes.

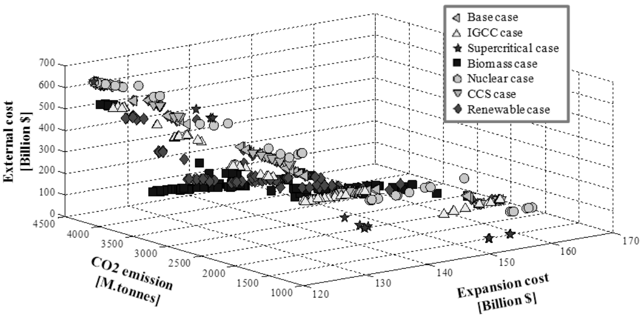

Figure 3. Pareto optimal fronts of all cases for three objective functions.

The plan corresponding to each objective is minimized individually by the MILP model of GAMS and the results for all cases are reported in the parentheses in Table 4. For each case study, several non-dominated plans are obtained. For example, the base case obtained 48 plans in Pareto front. All plans are ranked by the AHP score based on the AHP structure in Figure 2. All attributes of the plan with the highest AHP score for each cases including generation cost, CO_2 emission, external cost, EENS, coal and gas supply are reported in Table 4. In terms of least cost planning, the biomass case is the best case to reduce the generation and expansion cost. It is noted that biomass power deployment would provide 2.01% of the cost reduction from the base

Table 3. Pair-wise comparison of AHP for MOPGEP.

Main criteria	Economic	Environment	Reliability	Vulnerability
Economic	1	1/2	3	5
Environment	2	1	3	6
Reliability	1/3	1/3	1	2
Vulnerability	1/5	1/6	1/2	1

Environment sub-criteria	CO_2 emission	External cost
CO_2 emission	1	2
External cost	1/2	1

Vulnerability sub-criteria	Coal	Natural gas
Coal	1	3
Natural gas	1/3	1

Table 4. AHP score of case studies.

Case study	Highest AHP score	Number of plans in Pareto front	Attributes of the plan with the highest AHP score					
			Expansion cost [Billion $]	CO_2 emission [$MtCO_2$]	External cost [Billion $]	EENS [GWh]	Coal supply [Mt]	Gas supply [MM.scf/days]
Base case	0.414	48	165.35(121.86)	2,227.33(2,010.20)	135.06(92.46)	60.58	99.79	97,250
IGCC	0.425	133	162.88(121.50)	2,182.48(2,010.20)	96.96(82.78)	66.37	116.21	96,759
Supercritical	0.416	112	165.20(121.86)	2,225.32(2,010.20)	128.42(92.12)	60.49	110.78	96,934
Biomass	0.484	116	151.48(119.41)	1,801.15(1,801.15)	104.56(92.27)	60.36	7.90	89,984
Nuclear	0.487	49	160.98(121.86)	1,644.48(1,641.60)	84.18(83.18)	58.48	8.01	83,410
CCS	0.509	22	149.62(121.86)	964.42(946.20)	76.84(75.82)	76.32	1,025.45	34,105
Renewable	0.460	265	159.60(121.86)	1,997.78(1997.76)	93.36(92.28)	55.82	8.00	100,905
Least cost	0.244	-	119.41	3,745.66	574.99	64.62	1,092.92	23,866

case. The IGCC case indicates that efficiency improvement of IGCC resulting in replacement of coal-fired thermal power plant by IGCC technology, which can penetrate the power market by decreasing 360 million US dollars from the base case. For the other cases, the traditional fossil-based technologies, especially CC power plant, have been used in notable tendency to attain an economical power generation.

For making a substantial contribution to CO_2 emission mitigation, CCS generating technology outperforms most other power plants because of its own particularity. The CCS implementation would result in mitigation of CO_2 emissions by 74.7% (around 2.8 $GtCO_2$) from the least cost case. Since nuclear, biomass and renewable energy technologies have dominated over the fossil-based technologies in terms of CO_2 emissions, corresponding cases exhibit the great potentiality to curtail such emission in the power sector. The other cases entail that coal-fired technologies are unlikely to mitigate CO_2 emissions owing to higher carbon content of coal-to-electricity conversion. These cases are constrained to utilize the coal system which is displaced by the gas-fired CC for capacity expansion with low CO_2 emissions.

To minimize the negative externalities of power generation according to a "polluter pays principle" (Deroubaix and Leveque, 2006), CCS technology remains the most inexpensive plant in this objective. The external cost reduction of around 500 billion US dollars is achieved when CCS technology is incorporated into coal-fired technologies resulting in a total cost increment of 30 billion dollars. A thermal power plant, such as supercritical and biomass technologies, works on a conventional combustion process and thermodynamic cycle, having a dramatic effect on the high external cost due to more harmful emissions. IGCC and nuclear technologies without combustion process are the competitive candidate power plants in terms of low external cost. Renewable energy sources have almost zero negative externalities, but resource availability is limited.

As shown in Table 4, the best score of the supercritical case and the base case exhibit a low compromised plan when compared with the others due to the strongly desirable importance of environmental conservation in this study, whilst the CCS case indicates the most potential. The CCS case improves the average AHP score by 13.7% from the other cases to obtain the compromise of cost, environment and reliability as well as imported fuels.

The compromise among several criteria requires a cost increment to achieve several goals, different from the cost-related planning which optimizes only the total cost. Average cost of all cases is higher by 33.41% from the least cost planning. However, the proposed approach would make substantial contribution to environmental benefits by mitigating CO_2 emissions of 1863.3 $MtCO_2$ and reducing external cost of 102.8 billion US dollars. Furthermore, all cases, except IGCC and CCS cases, improve system reliability by 3.08%, when compared to the least cost planning. The average EENS of all cases is about 62.63 GWh over the entire planning horizon.

In terms of supply dependence, coal is not able to be the compromise among all criteria due to considerable pollutant emissions and other negative externalities. It is noted that coal-fired technologies are not selected by all compromise solutions which would consider the coal power when such a technology provides an abatement of environmental damage as in the CCS case. As a consequence of ignoring coal power, natural gas acts as the primary resource of most compromise solutions. Gas dependence is more than 85,000 MMscf/day because of its own compromise in nature, including moderate fuel cost as well as environmental damage.

6. Generation Mix

Generation mix in planning horizon for all compromise cases and the least cost planning are portrayed in Figure 4. In the figure, the term "new technology" refers to the candidate technology which corresponds to the case. For example, in nuclear case, new technology denotes the nuclear power plant.

From the least cost plan, the TH-Coal would be required up to 37,717 MW by the year 2030, which becomes the largest contributor to electricity production, and accounted for 57% of the total power generation. CC-Gas plays a less important role for reducing the cost of electricity

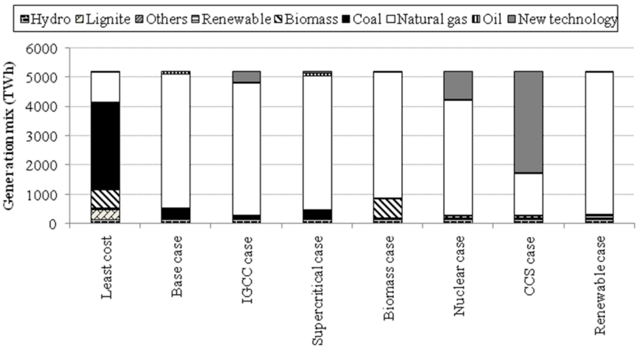

Figure 4. Generation mix for entire planning horizon.

production. This, biomass-fired station is suggested to expand as fast as possible due to its own competitive capital and generation cost. Furthermore, the lignite-fired technology is only selected in the least cost plan.

In the proposed compromise planning, conventional TH-Coal would not increase as much as in the least cost model. The other candidate technologies such as CC-Gas, IGCC-Coal, biomass, nuclear and CCS technologies are supplanted TH-Coal in the other cases. Results indicate that the CC-Gas is the most compromise decision among the criteria. More than three quarters of total electricity production will be obtained from gas-to-electricity conversion in IGCC, supercritical, biomass, nuclear and renewable case. When more plants are taken into account, the gas-fired technology will decrease depending on potential of such a plant to reduce the imported natural gas dependency. In the IGCC, renewable, supercritical and base case, the generation proportion manifests a significant resemblance with each other in utilization of the CC-Gas which shares more than 87% of total electricity production.

Reduction in gas-fired intensity in the power sector can be acquired from nuclear and biomass cases. Subject to the constraint in the nuclear case, nuclear power plant is fully selected to be installed and generate electricity, by 959.75 TWh in planning horizon. Although scarcity of agricultural yields and plantation area is the major constraint on development of biomass technology, like nuclear case, the expansion plan in the biomass indicates that the increasing biomass-fired generation will supplant CC-Gas of 652.29 TWh.PV, wind and small hydro power are unreliable to produce a sufficient generation because the renewable energy is contingent on physical geography conditions, a low availability factor and a high capital cost. The expansion plan in the renewable case will augment less than 897 MW of such a renewable energy with respect to the constraint on the potential of renewable resource in Thailand. The selected generation pattern will be rather identical to the IGCC case.

The most interesting point to note is that in CCS case the inauguration of CCS technologies results in an appreciable evolution of capacity and generation configuration from the other case studies. Therefore, the CCS technology is required for 52,200 MW of installed capacity, and accounted for 66% of the total generation.

7. Conclusion

In this study, a multi-objective optimization and multi-criteria decision making model is developed to solve the MOPGEP problem. Three objective functions are formulated for minimizing power generation expansion cost, CO_2 emissions and external costs simultaneously. The hybrid approach of multi-objective evolutionary algorithm and deterministic optimization and decomposition technique are incorporated in order to improve the optimization performance for handling large-scale problem. The solution is ranked by using AHP method and then the most suitable solution is obtained. The final decision is arrived at by considering four criteria; namely, economics, environment, reliability and vulnerability. For power generation in Thailand, the results indicate that natural gas will be the resource among three objectives with the highest compromise and lead to severe imported gas dependency in the future. Promoting coal-fired generation with CCS would be a solution to provide inexpensive reduction of environmental damage and gas dependence. The contribution to environmental benefits would be achieved by mitigating CO_2 emission of 1863.3 $MtCO_2$ from the consequence of the only-cost-concerned plan. Finally, in practice, the proposed framework is recommended to be applied to Thailand in order to solve the energy-environment-economic problem.

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