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Multi-Objective Optimization of Integrated Power System Expansion Planning with Renewable Energy-Based Distributed Generation

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Abstract – *Multi-objective-based power system expansion planning considering distributed generation is presented in this study. An integrated model of electrical power system expansion planning with renewable energy-based distributed generation is proposed. Two objective functions, cost and the emission objective function, are implemented in the proposed model. The cost function comprises investment cost and operation cost. The investment cost covers the cost of the new generation unit, the new distributed generation unit, and the investment for the new transmission circuit. The operation cost covers the operation cost of the installed and new generation unit and the operation cost of the installed and new distributed generation unit. Two emission gasses, CO_2 and NO_x, are considered in the proposed model. These two gasses are expressed in the same unit as Global Warming Potential. The developed model is implemented into the IEEE 14 bus system. Lexicographic optimization combined with the epsilon constraint technique is used to solve the multi-objective problem. A Pareto optimal solution is generated by this method. Then, the fuzzy decision-making process is implemented to select the best solution from the Pareto set. The simulation results show that the distributed generation significantly reduces the overall cost of power system expansion planning. With a 30% DG penetration level, overall planning costs can be reduced by 12.62% compared to without DG penetration with an equal weighting factor for each objective function. Details of the capacity expansion of the generation unit, distributed generation unit, and transmission line are presented in this study.*

***Keywords**: Multi-Objective, Generation Expansion, Transmission Expansion, Integrated Planning, Distributed Generation, Lexicographic Optimization, Epsilon Constraint*

Nomenclature

n	Number of buses
l	Line index connected bus i and bus *j*
el	Subset of *l* for existing line
nl	Subset of *l* for new line
gt	Technology of generation unit
ng	Number of generation unit
go	Capacity option of generation unit
nc	Number of parallel line
dgt	Technology of DG unit
ndg	Number of DG unit
dgo	Capacity option of DG unit
o	Demand operating hour
$EPGMax_{i,gt}$	The maximum capacity of installed generation unit on each bus and technology
$EPDGMax_{i,dgt,ndg}$	The maximum capacity of existing DG unit for each bus, technology, and DG number
$NGCost_{gt,go}$	Investment cost new generation unit for each technology and capacity option
$NDGCost_{dgt,dgo}$	Investment cost of new DG unit for each DG technology and capacity option
$NLCost_{i,j}$	Investment cost of new line connected bus *i* to bus *j*
$GvarCost_{gt}$	Variable OM cost for each technology of generation unit
$GFixCost\_gt$	Fixed OM cost for each technology of generation unit
$DGvarCost_{gt}$	Variable OM cost for each technology of DG unit
$DGFixCost\_gt$	Fixed OM cost for each technology of DG unit
$PDMax_{i,o}$	Maximum demand power in each bus and operating hour
$NPGCapOpt_{gt,go}$	Capacity option of each generation technology
$NPDGCapOpt_{dgt,dgo}$	Capacity option of each DG technology
BL_l	Susceptance of line *l*
N_l	Number of existing parallel circuit of line *l*
$PLMax_l$	Maximum capacity of line *l*
$MaxRM$	Maximum reserve margin

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$Elec_{i,gt,ng}$	Electricity production by generating on each bus, technology, and generation number
$ElecDG_{i,dgt,ndg}$	Electricity production by DG on each bus, technology, and DG number
$CapFac_{gt}$	Capacity Factor of each generation unit technology
$DGCapFac_{dgt}$	Capacity Factor of each DG unit technology
MOH_{gt}	Maximum operation hour of each generation unit technology
$DGMOH_{dgt}$	Maximum operation hour of each DG unit technology
POR_{gt}	Planned outage rate of each generation unit technology
FOR_{gt}	Forced outage rate of each generation unit technology
$DGPOR_{dgt}$	Planned outage rate of each DG unit technology
$DGFOR_{dgt}$	Forced outage rate of each DG unit technology
$UG_{i,gt,ng,go}$	Binary variable of new generation unit
$UT_{i,j,nc}$	Binary variable of new transmission line
$UDG_{i,dgt,ndg,dgo}$	Binary variable of new DG unit
$EPG_{i,gt,o}$	Capacity production of existing generation unit for each bus, technology, and operating hour
$NPG_{i,gt,ng,o}$	Capacity production of newly built generating unit for each bus, technology, and operating hour
$EPDG_{i,dgt,o}$	Capacity production of existing DG unit for each bus, technology, and operating hour
$NPDG_{i,dgt,ndg,o}$	Capacity production of newly built DG unit for each bus, technology, and operating hour
$NPGMax_{i,gt,ng}$	The maximum capacity of newly built generation unit for each bus, technology, and generation number
$NPDGMax_{i,dgt,ndg}$	Maximum capacity of newly built DG unit for each bus, technology, and DG number
$PL_{l,o}$	Power flow through line *l* for each operating hour

I. Introduction

Population growth and a growing economy are two factors that drive the demand for electricity. Electricity companies should address this increasing need by planning and expanding the capacity of the power system. The goal of meeting the increasing demand for electricity is the primary objective in power system expansion planning. On the other hand, environmental stress is an additional challenge that also should be considered by electricity companies. Therefore, power system expansion costs and environmental impacts in the form of carbon dioxide (CO_2) and Nitrous Oxide (NO_X) emissions should be simultaneously addressed. Single objective optimization methods are commonly used to solve generation expansion planning (GEP), transmission expansion planning (TEP), and the combination of generation and transmission expansion planning (G&TEP). The most common objective of optimization is to minimize the total cost of power system expansion.

The total cost of power system expansion generally consists of the investment cost of the new generation units and the new transmission lines and the operation cost of the installed and new generation units.

Modification of power system expansion planning incorporating fuel transportation costs was published in [1]. This study presented additional constraints related to fuel availability which is the capacity of fuel transportation from the fuel sources to each generation units. The short-term operation cost of a generation unit and annual reliability as a sub-problem were introduced in a power system expansion model in [2]. This study showed that operation costs could be reduced by considering a demand response in the model. The role of renewable energy sources, such as wind energy, was also considered to minimize the overall planning cost [3], [4].

The investment cost of transmission lines can be significantly reduced by sitting additional generation units in suitable locations. When a new generation unit is sited in a new location, new transmission lines must be installed which incurs a high cost, for example, for environmental clearance. A model to address this problem was discussed in [5]. The investment cost of a new transmission line can also be reduced by considering distributed generation (DG) in the planning model [6]. In this study, the investment cost of a transmission line was significantly reduced. In [7], DG implementation resulted in a different configuration of the transmission line. The environmental impact of power system expansion planning has been considered to be single objective optimization. Low carbon economy has been integrated into the GEP model by treating the emission factor as a constraint in the model [8], [9]. Moreover, the emission constraint has been taken into account at the operational level as the emission cost [10]. Reducing emissions by incorporating solar power plants was proposed in [11], [12]. Another method to reduce the environmental impact of a power system is to reduce growth in electricity demand. Reducing environmental impact can be achieved by implementing demand-side management (DSM) into the GEP model [13]-[16]. Several studies have presented single objective-based integrated power system planning with consideration to environmental impact. The sustainable aspects of G&TEP have been published in [17] with mention of the uncertainty of demand growth, greenhouse gas (GHG) emission, and fuel prices. This study expresses CO_2 emission as a social cost that is a part of the total cost of the objective function. Environmental impact in the form of SO_2 and NO_x has also been considered in a probabilistic G&TEP model [18]. Clean energy technology and DSM have been implemented as a CO_2 mitigation scenario in the G&TEP model in [19]. The implementation of DG in the G&TEP model has also been reported. In [20], DG capacity was determined by an optimization process. Then, the determined DG capacity was treated as a negative load to adjust electricity demand in the power balance equation. This equation was implemented in each node. DG was implemented in a simultaneous optimization model of G&TEP in [21]. This proposed model was a single objective optimization that considered environmental impact concerning CO_2, SO_2, and NO_x. Multi-objective approaches have recently been applied to the planning model of the power system expansion whether in the form of GEP, TEP, or G&TEP.

A multi-objective model of TEP that simultaneously minimizes cost and air emissions (CO_2 and NO_x) was published in [22]. This model was applied over the long-term planning horizon. In GEP, the generating technologies can be selected by considering economic and environmental criteria. The multi-objective model and analytic hierarchy process of GEP was utilized to accomplish this task in [23]. Another opposing parameter in power system expansion planning is minimizing investment and operation costs and reducing transmission loss. This problem was solved using multi-objective optimization and utilizing fuzzy decision making to select the most appropriate solution from the Pareto set [24]. The G&TEP model was implemented in this study. The main contributions of this study are:

1. A multi-objective framework is implemented in the G&TEP model. The two conflicting objective functions in this study are the cost of investment and operation and air emissions of CO_2 and NO_x.
2. The impact of DG on total planning cost, network configuration, and generated emission is analyzed for each DG penetration level.

The augmented epsilon method is used to minimize two objective functions. Then, the final solution is selected from the Pareto set using the fuzzy decision-making process.

II. Multi-Objective Problem Formulation

The objective functions of the proposed model are investment and operation costs and air pollution caused by the generating unit. These two objective functions are expressed in (1):

$$\text{Multi objective function} = \begin{cases} z^{cost}, & \text{Investment and operation costs} \\ z^{emission}, & \text{air pollution from gen. unit} \end{cases} \tag{1}$$

The following sections give a detailed description of the objective function z^{cost} and $z^{emission}$. The constraint functions of the model are briefly described in section II.3 to section II.7.

II.1. Investment and Operation Costs

The problem of cost minimization involves both investment cost and operation cost. Investment cost includes the generating unit, lines, and DG investment.

The investment cost is described in (2):

$$\begin{aligned} I^{cost} &= \sum_{i\in n}\sum_{j\in gt}\sum_{k\in ng}\sum_{l\in go} NGCost_{j,l}UG_{i,j,k,l} \\ &+ \sum_{p\in nl}\sum_{q\in nc} NLCost_p UT_{p,,q} \\ &+ \sum_{i\in n}\sum_{x\in dgt}\sum_{y\in ndg}\sum_{z\in dgo} NDGCost_{x,z}UDG_{i,x,y,z} \end{aligned} \tag{2}$$

Operation costs involve existing and newly built generation units and DG units. Equation (3) shows the overall variable operating costs and the overall fixed operation cost is given in (4):

$$\begin{aligned} VarO^{Cost} &= \sum_{i\in o} PDH_i \\ &\times \left\{ \left(\sum_{j\in n}\sum_{k\in gt} GVarCost_k \times \left(EPG_{i,j,k} + \sum_{l\in ng} NPG_{i,j,k,l} \right) \right) \right. \\ &+ \left. \left(\sum_{j\in n}\sum_{x\in dgt} DGVarCost_x \times \left(EPDG_{i,j,x} + \sum_{y\in ndg} NPDG_{i,j,x,y} \right) \right) \right\} \end{aligned} \tag{3}$$

$$\begin{aligned} FixedO^{Cost} &= \sum_{i\in n}\sum_{j\in gt} GFixCost_j \times \left\{ EPGMax_{i,j} + \sum_{k\in ng} NPGMax_{i,j,k} \right\} \\ &+ \sum_{i\in}\sum_{x\in dgt} GFixCost_x \times \left\{ EPDGMax_{i,x} + \sum_{y\in ndg} NPDGMax_{i,x,y} \right\} \end{aligned} \tag{4}$$

Finally, the objective function of cost minimization can be expressed as shown in (5) where I^{cost} is total investment cost, $VarO^{cost}$ is total variable operation cost, and $FixedO^{cost}$ is total fixed operation cost:

$$\min z^{cost} = I^{cost} + VarO^{cost} + FixedO^{cost} \tag{5}$$

II.2. Air Pollution of Power Plant Unit

The second objective function is air pollution that is caused by existing and newly built generation units. Two kinds of gases, CO_2 and NO_x, are considered in the proposed model. The minimization problem of the second objective function is expressed in (6). As shown in equation (6), a constant of 265 is used as the global warming potential (GWP) caused by NO_x. For CO_2, the value of GWP is 1 [25]:

$$\min z^{emission} = \sum_{i\in o} PDH_i \times \left\{\sum_{j\in n}\sum_{k\in gt}\left(CO_{2_k} + 265 \times NO_{x_k}\right) \times \left(EPG_{i,j,k} + \sum_{l\in ng} NPG_{i,j,k,l}\right)\right\} \tag{6}$$

II.3. Power Balance

The constraint of power balance should be met on each bus for all conditions during operating hours. This constraint can be expressed as shown in (7):

$$\sum_{k\in gt} EPG_{i,j,k} + \sum_{k\in gt}\sum_{l\in ng} NPG_{i,j,k,l} + \sum_{l|tb(l)=n} PL_l - \sum_{l|fb(l)=n} PL_l + \sum_{x\in dgt} EPDG_{i,j,x} + \sum_{x\in dgt}\sum_{y\in ndg} NPDG_{i,j,x,y} = PDMax_{i,j}, \forall(i\in n), \forall(j\in o) \tag{7}$$

II.4. Limitation of Power Generation

The production of electrical power is bound by the specific value of each technology of the generation unit. Equations (8) and (9) show the power production limit for existing and newly built generation units, respectively:

$$MinEPG_{i,j} \le EPG_{i,j,k} \le MaxEPG_{i,j}, \forall(i\in n), \forall(j\in gt), \forall(k\in o) \tag{8}$$

$$MinNPG_j \le \sum_{l\in ng} NPG_{i,j,k,l} \le \sum_{l\in ng} NPGMax_{i,j,l}, \forall(i\in n), \forall(j\in gt), \forall(k\in o) \tag{9}$$

$NPGMax_{i,gt,ng}$ is a decision variable of the maximum installed capacity of newly built generation units. This variable is defined in (10) and $UG_{i,gt,ng,go}$ is a binary decision variable that is defined in (11). This binary variable will have a value of 1 if any technology with a specific capacity option of generation unit must be built and 0 if otherwise:

$$NPGMax_{i,j,k} = \sum_{l\in go} NPGCapOpt_{k,l} UG_{i,j,k,l}, \forall(i\in n), \forall(j\in gt), \forall(k\in ng) \tag{10}$$

$$\sum_{l\in go} UG_{i,j,k,l} \le 1, \forall(i\in n), \forall(j\in gt), \forall(k\in ng) \tag{11}$$

Power generation by the DG unit is also considered.

The constraint functions related to DG power generation are expressed in (12) and (13). The operation of these constraints is the same as the constraints for the generation unit:

$$NPDGMax_{i,j,k} = \sum_{l\in dgo} NPDGCapOpt_{j,l} UDG_{i,j,k,l}, \forall(i\in n), \forall(j\in dgt), \forall(k\in ndg) \tag{12}$$

$$\sum_{l\in dgo} UDG_{i,j,k,l} \le 1, \forall(i\in n), \forall(j\in dgt), \forall(k\in ndg) \tag{13}$$

All the generation units, both those that are already installed and those that are newly built, must meet the maximum reserve margin requirement. The constraint relates to the maximum reserve margin is shown in (14):

$$\sum_{i\in n}\sum_{j\in gt} EPGMax_{i,j} + \sum_{i\in n}\sum_{j\in gt}\sum_{k\in ng} NPGMax_{i,j,k} \ge (1 + MaxRM)\sum_{i\in n}\sum_{m\in o|o=peak} PDMax_{i,m} \tag{14}$$

II.5. Limitation of Electricity Generation

Electricity production strongly depends on the availability of the generation and DG units and their capacity factors. The constraints related to electricity generation by each technology of the generation unit and DG unit is expressed in (15) and (16) respectively. The maximum operating hours for each generation unit technology and DG unit technology is described in (17) and (18). The constraint in (19), which is related to satisfying the total demand for electricity (TDE) must be met.

$$Elec_{i,j,k} \le CapFac_j MOH_j\left(EPGMax_{i,j} + NPGMax_{i,j,k}\right), \forall(i\in n), \forall(j\in gt), \forall(k\in ng) \tag{15}$$

$$ElecDG_{i,j,k} \leq DGCapFac_j DGMOH_j \left(EPDGMax_{i,j} + NPDGMax_{i,j,k}\right), \quad \forall(i \in n), \forall(j \in dgt), \forall(k \in ndg) \tag{16}$$

$$MOH_i = 8760\{1 - (POR_i + FOR_i)\}, \forall(i \in gt) \tag{17}$$

$$DGMOH_i = 8760\{1 - (DGPOR_i + DGFOR_i)\}, \quad \forall(i \in dgt) \tag{18}$$

$$\sum_{i\in n}\sum_{j\in gt}\sum_{k\in ng} Elec_{i,j,k} + \sum_{i\in n}\sum_{x\in dgt}\sum_{y\in ndg} ElecDG_{i,x,y} \geq TDE \tag{19}$$

II.6. Penetration Level of DG

The penetration level of DG is based on maximum power demand in each bus. The main aim of the implementation of the DG penetration level is to propose a method to determine DG capacity that will result in the most economic power system expansion planning. The constraint in (20) implements the DG penetration level. In this study, a parameter of $DGPen$ is selected for 10%, 20%, and 30% with respect to the maximum power demand in each bus:

$$\sum_{x\in dgt}\sum_{y\in ndg} NDGMax_{i,x,y} + \sum_{x\in dgt} EPDGMax_{i,x} \leq DGPen \times PDMax_{i,j}, \quad \forall(i \in n), \forall(j \in o) \tag{20}$$

II.7. Line Power Flow

In most of the power system planning publications, a model of power flow is implemented as a DC model with the assumption that there is no loss in the transmission line. The use of the DC model reduces complexity and computational time burden. The constraint in (21) and (22) expresses the power flow with the DC model for existing and new transmission lines, respectively. The maximum flow of the power line is limited to constraint (23) and (24). It should be noted that UT is only defined for the candidate transmission line:

$$PL_{i,j} = BL_i \cdot N_i\left(\theta_{l|l.fb=i,j} - \theta_{l|l.tb=i,j}\right), \quad \forall(i \in el), \forall(j \in o) \tag{21}$$

$$-M\left(1 - UT_{i,k}\right) \leq PL_{i,j,k} - BL_l\left(\theta_{l|l.fb=i,j} - \theta_{l|l.tb=i,j}\right) \leq M\left(1 - UT_{i,k}\right), \quad \forall(i \in nl), \forall(j \in o), \forall(k \in nc) \tag{22}$$

$$-PLMax_i \leq PL_{i,j} \leq PLMax_i, \quad \forall(i \in el), \forall(j \in o) \tag{23}$$

$$-PLMax_i UT_{i,k} \leq PL_{i,j,k} \leq PLMax_i UT_{i,k}, \quad \forall(i \in nl), \forall(j \in o), \forall(k \in nc) \tag{24}$$

III. Multi-Objective Optimization Method

The multi-objective optimization problem (MOOP) can be solved using lexicographic optimization combined with the epsilon constraint technique. Then, the best solution is selected from the set of generated Pareto optimal solutions using the fuzzy decision-making process.

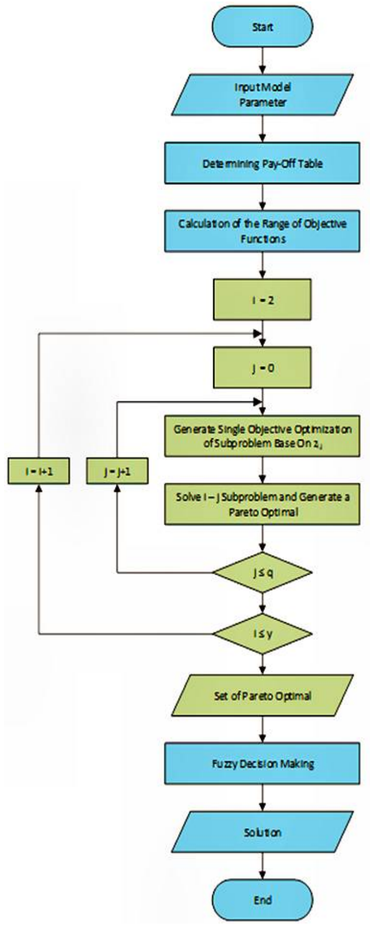


Fig. 1. Flowchart of the proposed method for the MOOP problem

III.1. Solution Method of Multi-Objective Optimization

MOOP can be formulated based on the augmented epsilon constraint method as described in (25). A brief explanation of the implementation of this method in power system expansion planning is given in [26]:

$$\frac{\text{Min}}{\text{Max}}\left[z_1(x) + dir_1 r_1 \sum_{i=2} \frac{S_i}{r_i}\right] \quad s.t. \quad z_i(x) - dir_i S_i = e_i, \forall S_i \in R^+, i = 2,3,\ldots,y \tag{25}$$

The objective function number is represented by y.

The direction of the objective function is symbolized by dir_i. For the minimization process, the value of dir_i is -1 and dir_i is equal to +1 to represent that the process of optimization is maximized. The parameter of e_i is used to ensure an efficient solution to the problem. The value of

e_i is iteratively varied. In an optimization problem, there will be some slack or surplus variables. In (25), these variables are expressed by S_i. This formulation is called the augmented epsilon constraint because of the presence of a second term of MOOP, $r_i \frac{S_i}{r_i}$, that is used to eliminate any scaling problem. The efficient solution that is generated by this method is proven in [27].

III.2. Fuzzy Decision Making

A decision should be selected from a generated set of Pareto optimal solutions. One of the most common techniques is fuzzy decision making (FDM). The implementation of fuzzy decision making in an electrical power system can be found in [28] and [29]. FDM technique uses the definition of linear membership functions for each objective function. A set of membership functions is defined in (26) and (27) for minimization and maximization problems, respectively. z_i^r is the rth Pareto optimal solution related to the membership function μ_i^r:

$$\mu_i^r = \begin{cases} 1, & z_i^r \leq z_i^{Min} \\ \dfrac{z_i^{Max} - z_i^r}{z_i^{Max} - z_i^{Min}}, & z_i^{Min} \leq z_i^r \leq z_i^{Max} \\ 0, & z_i^r \geq z_i^{Max} \end{cases} \tag{26}$$

$$\mu_i^r = \begin{cases} 0, & z_i^r \leq z_i^{Min} \\ \dfrac{z_i^r - z_i^{Min}}{z_i^{Max} - z_i^{Min}}, & z_i^{Min} \leq z_i^r \leq z_i^{Max} \\ 1, & z_i^r \geq z_i^{Max} \end{cases} \tag{27}$$

The overall membership function, μ^r, is defined based on its individual membership and is expressed in (28) where w_i is the weighting of ith objective function and y represents the objective function number. The value of μ^r is used by the decision maker to select the best solution from the set of Pareto optimal solutions. The best solution is indicated by the highest value of μ^r with particularly defined weighting factors. A method to solve MOOP based on the epsilon constraint technique and fuzzy decision making for the proposed model of power system expansion planning is shown in Fig. 1 as a flowchart. The process of the method can be described as follows.

Step 1: the pay-off table is generated by implementing a lexicographic optimization to MOOP. The pay-off table is a $m \times m$ table. The values generated by the objective function z_i will be the element of ith column of the pay-off table:

$$\mu^r = \frac{\sum_{i=1}^{y} w_i \mu_i^r}{\sum_{i=1}^{y} w_i} \tag{28}$$

Step 2: Determine the range for the objective functions z_i ($i = 2,3,\dots,y$). The range is calculated by (29):

$$r_i = z_i^{Max} - z_i^{Min} \tag{29}$$

Step 3: the range of $y-1$ objective function is separated into the same intervals q_i ($i = 2,3,\dots,y$).

Step 4: the MOOP method is implemented to solve the feasible optimization subproblem. The Pareto optimal solution is generated, and the infeasible subproblem is rejected.

Step 5: the fuzzy decision-making process is implemented to select the most desired solution based on generated Pareto optimal set.

IV. Results and Discussions

The proposed model of power system expansion planning with renewable energy-based DG is simulated using ODH-CPLEX 3.2 solver of the Advanced Multidimensional Modelling System (AIMMS) software.

The modified system of IEEE 14 buses is used to validate the proposed model. The mixed integer programming (MIP) relative optimality tolerance is set to 10^{-4}.

IV.1. Modified IEEE 14 Buses

The detailed configuration of the modified IEEE 14 bus system is shown in Fig. 2.

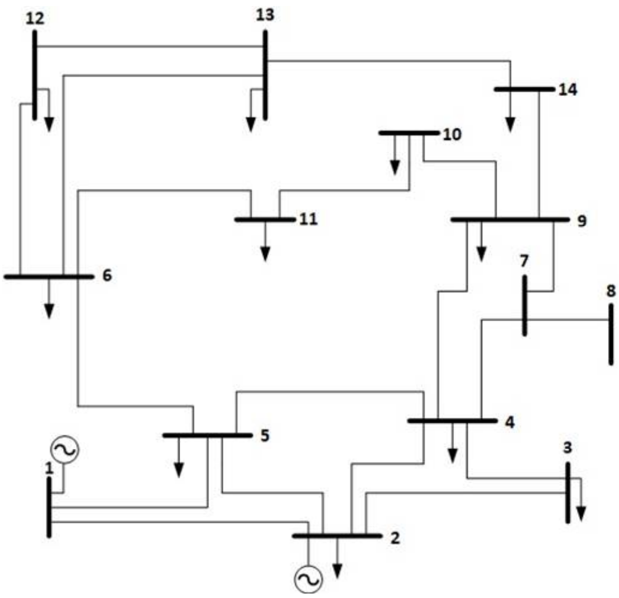


Fig. 2. Modified IEEE 14 Bus systems

The modified IEEE 14 bus system consists of two existing generation units located in bus 1 and bus 2 with a technology type of pulverized coal (PC) and natural gas combined cycle (CC) respectively. There are four possible locations to build a new generation unit which is on bus 4, bus 6, bus 8, and bus 10. The hydro generation unit can only be installed on bus 4 with a capacity limit of 100 MW. Another renewable energy-based generation unit, the geothermal potential with a capacity limit of 50

MW, can be added on bus 10. Details on the existing generation unit and characteristics of the candidate generation unit data are presented in Table A1 and Table A2 in Appendix [30], respectively. DG technology in this simulation is solar energy technology and wind energy technology. Solar energy technology is in the form of a non-tracking utility photovoltaic (PV) panel of 10 MW and an onshore wind turbine (WT) is used in the simulation. All buses, except bus 1, bus 7, and bus 8, are connected to a demand load. Details on the data of the loads and the existing lines are presented in Table A3 and Table A4 in Appendix, respectively. There are eight possibilities for adding a new line to the system. Table A5 shows detailed data on the candidate lines.

IV.2. Pareto Set and Decision Making

The Pareto optimal solution proposed MOP model is solved using the lexicographic and epsilon constraint method. The first objective function, i.e., cost minimization, is considered the primary objective function in the epsilon constraint method. To generate a set of Pareto optimal solutions, 50 (q_2 = 50) grid points are selected, and the proposed model is solved 50 times to generate the set of Pareto optimal solutions. By using the lexicographic, the obtained pay-off table is presented in (30):

$$\phi = \begin{bmatrix} z_1^{Min} & z_2^{Max} \\ z_1^{Max} & z_2^{Min} \end{bmatrix} = \begin{bmatrix} 367.58 & 930{,}535.58 \\ 2{,}113.30 & 311{,}120.92 \end{bmatrix} \quad (30)$$

The first column is related to the first objective function ($z_1 = z^{Cost}$) and the second is related to the emission objective function ($z_2 = z^{emission}$). The result of the cost objective function is in terms of millions of USD while the result of the emission objective function is in terms of tons of CO_2 Equivalent (CO_2 Eq.).

The result of the individual optimization is presented as the main diagonal of the pay-off table. It can be seen that a single objective function of $z^{the\ Cost}$ results in minimum cost but it generates maximum emissions. Conversely, the result from the single objective function of $z^{emission}$ results in minimum emissions but maximum cost. It can be seen from the pay-off table that the power system planner can reduce the planning cost to 367.58 million USD, but the emissions increase to 930,535.58 Ton CO_2 Eq. On the other hand, the planner can minimize emissions to 311,120.92 Ton CO_2 Eq. however, with a higher planning cost of 2,113.30 million USD. The best solution can be selected using fuzzy decision-making. Then, the planner is able to decide which Pareto optimal solution will be used as the final solution. The sets of Pareto optimal solutions for different levels of DG penetration are presented in Fig. 3.

For 0% of DG penetration, there is an infeasible solution when the emission value is minimum. It can be seen from the figure that increasing the level of DG penetration reduces the overall planning cost for each point of emission.

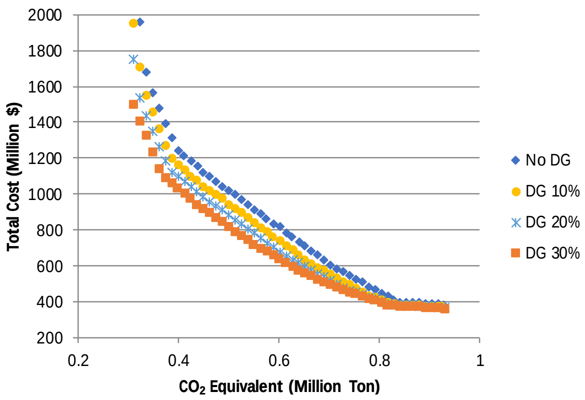
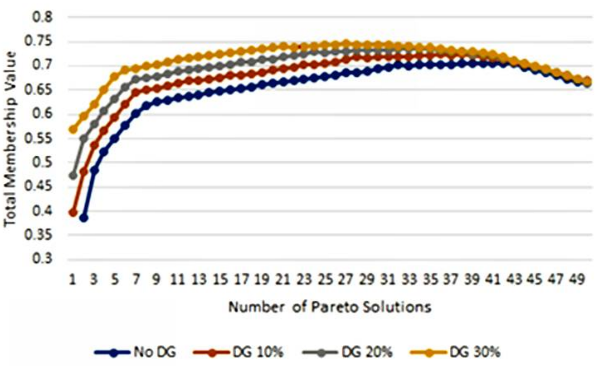


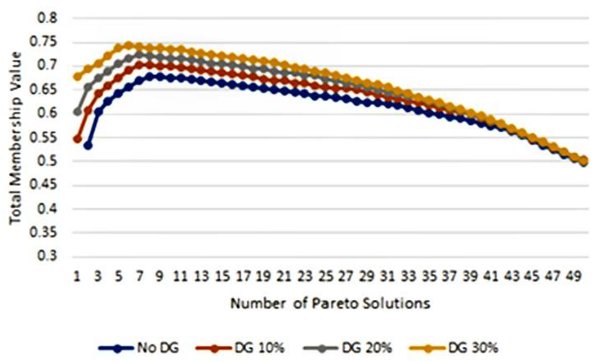
Fig. 3. Sets of Pareto optimal solutions generated by the epsilon constraint technique for different levels of DG penetration

At the point of minimum cost, the total emissions generated by the generation unit are increasing for all DG penetration levels. Increasing the DG penetration level will change the option of optimal decisions to select a combination of cheaper generation units and results in increased emissions. On the far end of the emission axis, it can be seen the solution of Pareto for each level of DG penetration will result in nearly the same overall planning cost. At this part of Pareto sets, increasing DG penetration level almost does not affect the overall cost of power system planning. On the other hand, increasing DG penetration level has a significant effect when emission strictly limited. Emissions generated by the generation unit will be at the minimum value when the planning cost is maximum. Hence, the final decision will be based on the minimum emission value that is emitted by the overall generation unit. A careful compromise should be reached between the overall planning cost and total emissions taking into consideration government regulations. The best solution can be chosen by implementing the fuzzy decision-making process. There are two weighting factor combinations of objective functions presented in this study, a weighting combination with more consideration to the cost objective function ($w_1 = 2$ and $w_2 = 1$) and an equal weighting factor (w_1 and $w_2 = 1$). The total membership value of the first and the second combinations are presented in Figs. 4(a) and (b). For each DG penetration level, the highest value of total membership is the best solution for the MOOP problem.

From Figs. 4, the selected solutions with $w_1 = 2$ and $w_2 = 1$ are Pareto solution numbers 42, 38, 34, and 27 for 0%, 10%, 20%, and 30% DG penetration levels, respectively. For the equal weighting factor, w_1 and $w_2 = 1$, the selected solutions are Pareto solution numbers 8, 7, 7, and 6 for 0%, 10%, 20%, and 30% DG penetration levels, respectively. With both combinations of weighting factors, total emission for each DG penetration level can be reduced. With $w_1 = 2$ and $w_2 = 1$, total emission can be reduced to 0.64 Million Ton CO_2 Eq. with 30% DG penetration level. Without DG penetration, the total generated emission is 0.83 Million Ton CO_2 Eq. when cost objective function has more attention compares to emission objective function.

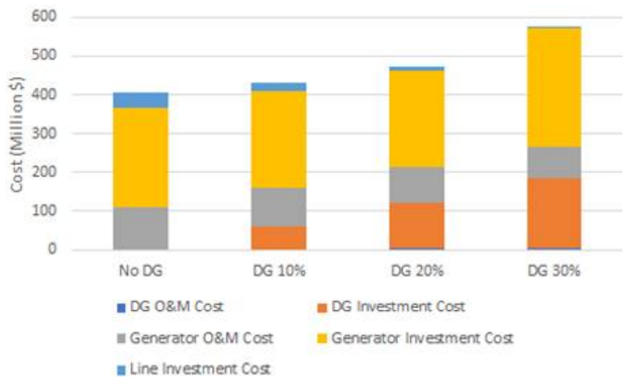


(a)

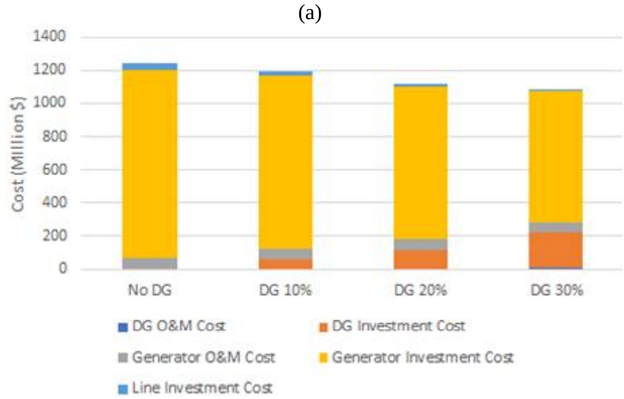


(b)

Figs. 4. Total membership value for each DG penetration level for a different combination of weighting factors



(a)



(b)

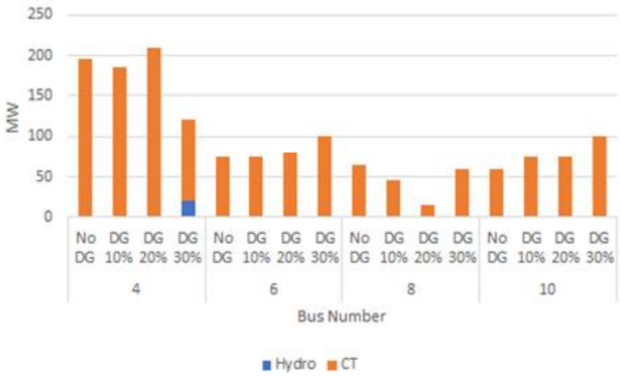
Figs. 5. Overall planning cost for each DG penetration level and different weighting factors

On the other hand, the overall planning cost is higher with increased DG penetration level. Without DG, overall planning cost is 405.56 Million USD while with 30% of DG penetration level overall planning cost is increased to 574.86 Million USD. By implementing equal weighting factors for both objective functions, the overall planning cost and the total emission can be reduced by increasing DG penetration level. With no DG penetration, needed planning cost and emitted air pollution is 1,241.59 Million USD and 0.40 Million Ton CO_2 Eq. respectively. By implementing a 30% DG penetration level, 12.62% and 6.27% reduction can be achieved for the overall planning cost and total emission respectively. In another word, 30% DG penetration level produced the overall planning cost and the total emission of 1,084.86 Million USD and 0.37 Million CO_2 Eq. respectively. Based on the selected solution, the overall planning cost is presented in Figs. 5. In the figures, WC1 is the weighting factor combination where $w_1 = 2$ and $w_2 = 1$ and WC2 is w_1 and $w_2 = 1$. From Fig. 5(b), it can be seen that the higher the DG penetration, the lower the planning costs for WC2. It also can be seen that increasing the DG penetration level has a significant impact on the investment cost of the transmission line. It can be concluded that it is more efficient to meet demand by building the generation unit as close as possible to the load center. Figs. 5 also give an intuitive solution where a better emission target can be achieved with lower overall planning cost by implementing a 20% or 30% DG penetration level on w_1 and $w_2 = 1$.

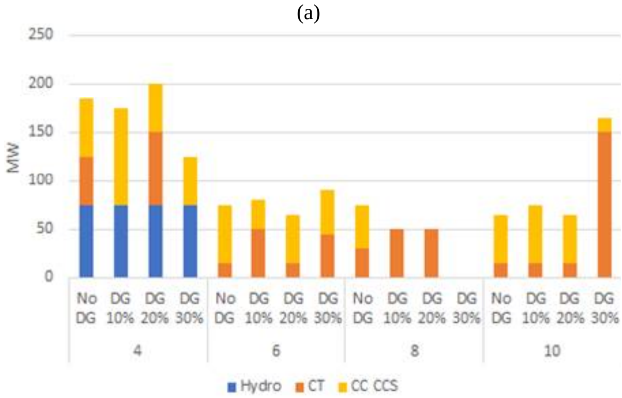
An opposite result is produced by the implementation of WC1 where cost objective function has more attention compared to emission objective function. As seen in Fig. 5(a), increasing DG penetration level produced a higher cost of power system planning. WC1 has the same impact compared to WC2 in term of the investment cost of the transmission line. The overall planning cost and the total emission with 30% DG penetration level is 574.86 Million USD and 0.64 Million Ton CO_2 Eq. respectively. By implementing a 30% DG penetration level, the total emission can be reduced by 22.98%. However, 30% DG penetration level with WC1 resulted in higher overall planning cost by 1.41% compared to the overall cost without DG.

IV.3. Power System Expansion Planning

Based on the results of fuzzy decision-making, an additional generation unit, DG unit, and transmission line can be selected. The new generation unit that should be added to the system on each bus is presented in Fig. 6(a) for WC 1 and (b) for WC2. It can be observed from the figure that assigning a different weighting factor will result in a different combination of added generation units. As shown in Fig. 6(a), two types of generation units are selected when the cost objective function has more weighting factors than the emission objective function (WC1). These types of generation units are natural gas combustion turbine (CT) and a hydropower plant.



(a)



(b)

Figs. 6. Added generation unit on each bus with different weighting factors

Without DG penetration, total install capacity of generation unit is 395 MW that consisted of CT type power plant. By increasing DG penetration level to 30%, hydropower plant of 20 MW has to be installed to meet the target of environmental constraint. In total, 380 MW of power plant capacity has to be built with 30% DG penetration level that consisted of hydropower plant of 20 MW and CT power plant of 360 MW.

After applying an equal weight factor for both objective functions, cleaner power plant technologies are selected, such as hydro and natural gas combined cycle with CCS (CC CCS). This is shown in Fig. 6(b). A hydropower plant is built to its maximum available capacity. In combination with other cleaner technologies, the hydropower plant is able to meet previously defined emission constraints. It can be observed that the CT power plant has more capacity when the DG penetration level is increased. To compensate for the emissions caused by the CT power plant, the capacity of the added DG unit is increased. Therefore, there is a compromise between the two conflicting objective functions, which are cost, and emission. The total capacity of the added generation unit based on generation technology is presented in Fig. 7. It is evident that the implementation of WC2 selected cleaner technology of generation unit to be installed in the system. WC2 exploited hydropower potential to its available capacity in all DG penetration level that is 75 MW. On the other hand, WC1 selected only 20 MW of hydropower with 30% DG penetration level.

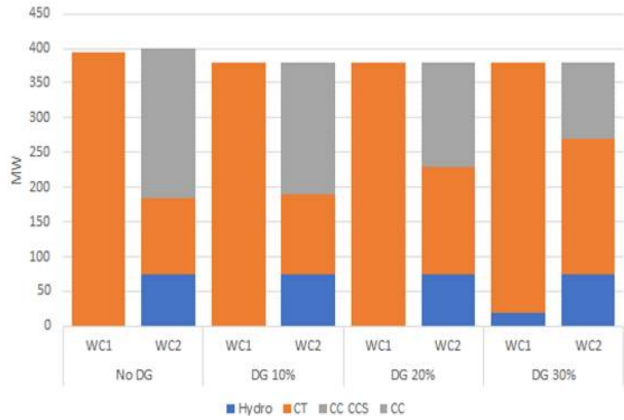


Fig. 7. The total capacity of the added generation unit to the system for different weighting factors

It also can be seen from the figure that the CT power plant is dominating generation expansion planning for all DG penetration level. On the other hand, WC2 produced less contribution than CT technology. The less selection compares to WC1 is caused by more attention to emission objective function.

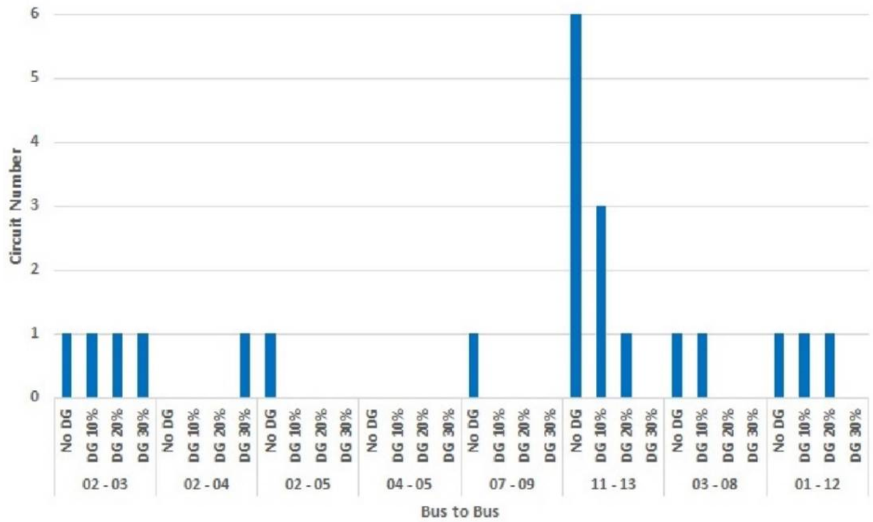
By the implementation of WC2, the total capacity of CT is 110 MW and 195 MW for DG penetration level of 0% and 30% respectively. CC with CCS technology has a lower capacity with increasing DG penetration level. With 30% DG penetration level, the capacity of CC with CCS is 110 MW while without DG penetration the capacity is 215 MW. For hydropower, the capacity reaches its maximum availability of 75 MW for all DG penetration level. The increasing of CT power plant caused more generated emission by all generation unit.

However, emission generated by the CT power plant is compensated by installed DG capacity. Figs. 8 show the addition of a new DG unit on each bus for different weighting factors (Fig. 8(a) for WC1 and Fig. 8(b) for WC2). The simulation results only select a DG unit of wind turbine (WT) technology. For all DG penetration levels and both WC, WT is mostly built on bus three while no DG is built on bus 10. The total added DG capacity for WC1 is 29 MW, 59 MW, and 91 MW with DG penetration levels of 10%, 20%, and 30%, respectively.

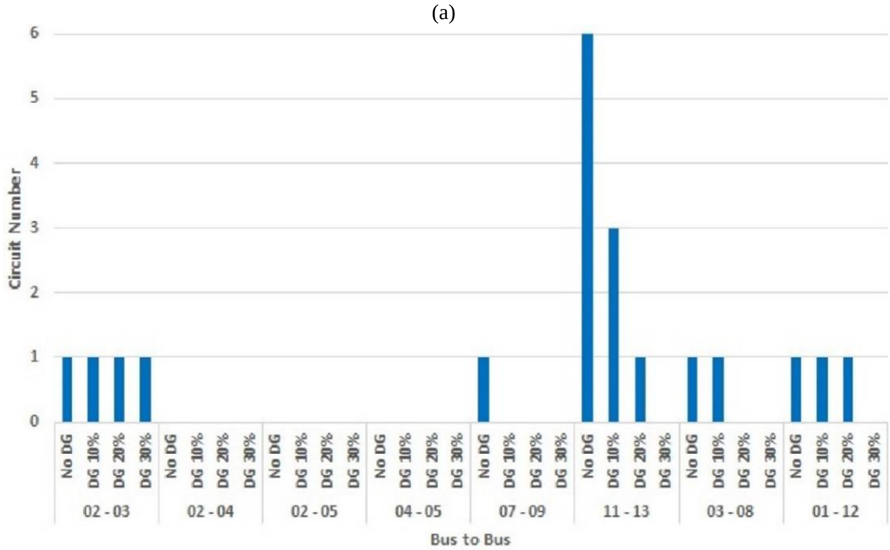
For WC2, where the weighting factor is equal for both objective functions, the added DG capacity for WT is 29 MW, 59 MW, and 90 MW with a DG penetration level of 10%, 20%, and 30%, respectively. Additionally, biomass DG technology is installed on bus 12 and bus 13 with each capacity of 5 MW. The additional transmission line that should be added in the system is shown in Fig. 9(a) and Fig. 9(b) for WC1 and WC2 respectively. As stated in the previous section, increasing DG penetration reduces the investment for the transmission line. As shown in Figs. 9, increasing the DG penetration level reduces the need for a new transmission line. The significant difference is shown in the circuit connected buses 11–13. With no DG penetration level, an additional six parallel lines are needed, for both WC1 and WC2.

(a) (b)

Figs. 8. Added DG unit on each bus with different weighting factors



(a)



(b)

Figs. 9. Added transmission line on each circuit with different weighting factors

With a 30% DG penetration level, no additional lines are needed in this circuit for both the WC1 and WC2 weighting factor. For 30% DG penetration level, WC1 resulted in only two additional circuits which are a circuit that connected bus 2 to bus 3 and a circuit that connected bus 2 to bus 4. Based on the difference of weighting factors, there is no circuit addition produces by WC2 for the corridors of bus 2 to bus 4 and bus 2 to bus 5. On the other hand, a circuit has to be added by the implementation of WC1 each for corridor bus 2 to bus 4 and bus 2 to bus 5.

V. Conclusion

A MOOP-based model of G&TEP with renewable energy-based DG was presented in this study. Two conflicting objective functions, cost and the emission objective function, were analyzed in the model. The developed model was implemented for the IEEE 14 Bus system to present the role of DG in power system expansion planning. Lexicographic optimization combined with the epsilon constraint technique is proposed in this study to solve the MOOP of G&TEP with DG. The proposed method generated a Pareto optimal solution followed by the fuzzy decision-making process to select the best solution from the Pareto set.

The simulation results indicate that increasing the DG penetration level reduces the overall cost of power system expansion planning. For WC1, increasing DG penetration level resulted in higher overall planning cost.

With 30% DG penetration level, the overall planning cost is 41.39% higher than the overall planning cost without DG penetration. On the other hand, WC1 produces lower emission by 22.98% with 30% DG penetration level compare to the emission without DG penetration. The overall planning cost and the total generated emission can be reduced simultaneously by the implementation of WC2. With 30% DG penetration level, the overall planning cost and the total emission can be reduced by 12.62% and 6.27% respectively. The proposed model is a static-deterministic model. This model can easily be modified to be a dynamic-deterministic model. Adding an uncertain variable is another enhancement to the proposed model. As significant cost reduction occurs for transmission expansion, further studies should consider the losses along the transmission line over the entire system.

Appendix

TABLE A1
EXISTING GENERATION UNITS OF MODIFIED IEEE 14 BUS

Bus	P^{min} MW	P^{max} MW	Fixed Cost $/kW-yr	Var. Cost $/MWh
1	20	100	42.1	4.6
2	20	80	11	3.5

TABLE A2
CHARACTERISTICS OF NEW GENERATION UNITS

Gen Tech.	Inv. Cost $/kW	Fixed Cost $/kW-yr	Var. Cost $/MWh	NOx Lb/MMBTU	CO_2 Lb/MMBTU	POR*) %	FOR**) %	Min. Load %
Coal Technology								
Pulverized Coal	2890	23	4	0.05	215	10	6	40
Pulverized Coal with CCS	6560	35.2	6.02	0.05	32	10	6	40
IGCC	3010	31.1	6.54	0.085	215	12	8	50
IGCC with CCS	6600	44.4	10.6	0.085	32	12	8	50
Natural Gas Technology								
Combustion Turbine	651	5.26	29.9	0.033	117	5	3	50
Combined Cycle	1230	6.31	3.67	0.0073	117	6	4	50
Combined Cycle with CCS	3750	18.4	10	0.0073	18	6	4	50
Nuclear								
Advance Pressurized Water Reactor	6100	127	-	-	-	6	4	50
Geothermal								
Enhanced Geothermal System	9625	-	31	-	-	2.41	0.75	
Biomass								
Biomass Standalone	3830	95	15	-	-	7.6		40
Hydropower Technology								
Hydroelectric Power Plant	3500	15	6	-	-	1.9	5	
Solar Energy Technology	2410	45				2	0	
Wind Energy Technology	1980	60				0.6	5	

*) Planned Outage Rate per Year
**) Forced Outage Rate per Year

TABLE A3
EXPECTED LOAD DATA

Bus Number	Expected Load (MW) Base Load	Expected Load (MW) Peak Load
2	23.90	32.55
3	103.75	141.30
4	52.64	71.70
5	40.20	54.75
6	27.97	38.10
9	32.49	44.25
10	35.46	48.30
11	27.86	37.95
12	16.96	23.10
13	15.20	20.70
14	16.41	22.35
Total Load	392.85	535.05

TABLE A4
EXISTING LINES DATA

Line	From Bus	To Bus	Line Impedance (p.u)		MVA Rating
			Resistance	Reactance	
1	1	2	0.0194	0.05917	120
2	1	5	0.0540	0.22304	65
3	2	3	0.0470	0.19797	36
4	2	4	0.0581	0.17632	65
5	2	5	0.0570	0.17388	50
6	3	4	0.0670	0.17103	65
7	4	5	0.0134	0.04211	45
8	4	7	0.0507	0.20912	55
9	4	9	0.1172	0.55618	32
10	5	6	0.0657	0.25202	45
11	6	11	0.0950	0.1989	18
12	6	12	0.1229	0.25581	32
13	6	13	0.0662	0.13027	32
14	7	8	0.0400	0.17615	32
15	7	9	0.0578	0.11001	32
16	9	10	0.0318	0.0845	32
17	9	14	0.1271	0.27038	32
18	10	11	0.0821	0.19207	12
19	12	13	0.2209	0.19988	12
20	13	14	0.1709	0.34802	12

TABLE A5
CANDIDATE OF NEW TRANSMISSION

From Bus	To Bus	Reactance (p.u)	Inv Cost (million $)	MVA Rating
1	12	0.19988	4.4	32
2	3	0.19797	4.1	36
2	4	0.17632	3.8	65
2	5	0.17388	3.6	50
3	8	0.27038	4	65
4	5	0.04211	3.9	32
7	9	0.11001	4.2	32
11	13	0.34802	3.4	12

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