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Electric power system generation expansion plans considering the impact of Smart Grid technologies

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ABSTRACT

In this research, we investigate how the electric power system generation expansion plans change and improve based on the availability of Smart Grid technologies. The new model specifically considers (i) the availability of Smart Grid technologies improving the performance of the distribution system, and/or (ii) the availability of the technologies shifting the demand from peak hours to off-peak hours. Multi-objective multi-period generation expansion planning problems are solved to determine the electricity generation technology options to be added, and where in the grid they should be constructed to simultaneously minimize multiple objectives such as cost and air emissions, e.g., CO_2. Unmet demand is also considered as a cost in the objective function so that the proposed approach considers the reliability of the system. The approach used here explicitly considers availability of the system components and operational dispatching decisions. Monte Carlo simulation is used to generate component availability scenarios, and then, the mixed-integer optimization problem is solved to find optimum expansion solutions considering these scenarios.

1. Introduction

The electricity generation expansion planning (GEP) problem involves the determination of the generation technology options (coal, wind, etc.) to be added to an existing power generation system, and the time and location where they should be installed to meet the growing energy demand over a planning time horizon. There have been many studies done to solve GEP problems. Although most of these studies focus on finding the least cost expansion plan, there are actually many conflicting objectives such as environmental impact, reliability, imported fuel, and so on. Moreover, there are uncertainties associated with the planning problem such as demand forecasts, input fuel prices, system component failure and others. Therefore, a multi-objective, stochastic optimization method is desirable to solve the GEP problem. In this research, we determine optimal expansion plan considering the availability of Smart Grid technologies.

Kagiannas et al. [1], Zhu and Chow [2], Hobbs [3], and Nara [4] provide a survey of modeling techniques developed for GEP. Malcolm and Zenios [5] propose an optimization model to produce robust power system capacity expansion under uncertain demand. Sirikum and Techanitisawad [6] and Park et al. [7] apply a GA-based heuristic to solve the least cost GEP problem. Bloom [8] and Firmo and Legey [9] apply generalized Benders' decomposition. Delgado et al. [10] propose a stochastic linear model to present how the nuclear generation options affect CO_2 emissions and the cost of the long-term generation system. Antunes et al. [11] models the GEP problem as a multiple objective mixed integer linear programming problem. Meza et al. [12] proposes a model for the multi-period multi-objective GEP problem. Meza et al. [13] presents a framework to determine the set of non-dominated solutions for single-period multi-objective mixed integer nonlinear GEP with Kirchoff's Law. Unsihuay-Vila et al. [14] presents a model for long term multi-objective expansion planning problem where the sustainable energy development criteria are integrated into the model. Falaghi et al. [15] provides a framework to solve multi-stage distribution expansion planning problem by using a combined genetic algorithm and optimal power flow as an optimization tool. Hemdan and Kurrat [16] provide a methodology to efficiently integrate the distributed generation to meet the increased load demand. Zerriffi et al. [17] compares the performance of centralized and distributed generation systems under various levels of stress using Monte-Carlo simulation.

There is an increasing desire to transform the current electric power system into a Smart Grid, defined by Amin and Stringer [18] as an intelligent system which consists of an autonomous digital system capable of identifying surges, downed lines and outages; resilient or "self-healing" which provides instantaneous damage control; flexible which is capable of accommodating new

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off-grid alternative energy sources; reliable which provides dynamic load balancing; and secure, minimizing vulnerability to terrorist or other attacks. The impacts and benefits of Smart Grid technologies can be summarized in three categories: (i) shift/reduce energy demand particularly during peak hours, (ii) increase the effective availability of the system components, and (iii) reduce energy losses during transmission and distribution. The Electric Power Research Institute (EPRI) states [19] that there will be $1.8 trillion in annual additive revenue by 2020 with a substantially more efficient and reliable grid. The Galvin Electricity Initiative states [20] that there will be reduction in power disturbance costs by $40 billion per year by means of a more reliable network. They also estimate that Smart Grid technological capabilities can be associated with a reduction in infrastructure investments by $46 billion to $117 billion over the next 20 years by the Smart Grid. National Renewable Energy Laboratory [21] estimates that the carbon emissions would rise from 1700 million tons of carbon per year today to 2300 by the year 2030 if nothing is done, but in the same study, they conclude that if energy efficiency programs are implemented and renewable energy sources are used, the carbon emission growth can be prevented and reduced to 1000 million tons of carbon by 2030. Based on these studies, it is possible to conclude that Smart Grid technologies can improve the electric energy value chain since these technologies can improve the network reliability and efficiency.

In this study, we minimize simultaneously multiple objectives, such as cost and air emissions, over a long term planning horizon under an uncertain environment. Monte-Carlo simulation is used to generate scenarios based on the uncertainty of availability of the system components. Selected scenarios are used to characterize the uncertainty of user demand and the availability of the system components, including generation units, transmission lines, distribution system, gas supplies, etc. Then, a two-stage stochastic programming model is used to solve the electricity generation expansion planning problem.

As a part of this paper, we also focus on investigating how Smart Grid technologies in the distribution system would affect the expansion plan. We mainly consider two classes of technologies; (1) technologies which can increase the availability of the distribution system components (circuit breakers, distribution lines, buses, etc.) and (2) technologies which can shift the demand from peak hours to off-peak hours. We approximate the availability of the distribution system by using minimal cut sets approach where the configuration is transformed into functionally equivalent series-parallel systems. We define cases with different levels of impact on the availability of the components and the amount of demand that is shifted.

2. Example electric power system topology

The topology for an existing central system studied here is the same as in Zerriffi et al. [17]. The existing system consists of central generation units distributed among ten power groups. These generation units have different technologies. The energy generated in these power groups is transmitted to the distribution system via transmission lines. Some of the generation units use natural gas as fuel. For those, we also consider the same natural gas network presented in Zerriffi et al. [17]. The transmission pipelines from natural gas storage feed the five power groups which contain natural gas burning generation units. When expanding or upgrading the electric grid, new generation technologies are either *distributed* or *centralized*. Historically, large centralized power generation units, such as nuclear or coal burning, were used. Distributed generation units are smaller units that can be located closer to the load so that long distance transmission from generation units to the distribution system is not necessary.

The breaker-and-a-half configuration with two diameters has been adopted as a basic design for supplying electricity from area grid to load blocks [22]. Fig. 1 shows the topology for the distribution system.

We approximate the unavailability of energy to the load blocks by using minimal cut sets. Minimal cut sets can be defined as a set of components that collectively prevent the energy to reach to the load blocks when they are not working. We used the minimal cut sets presented in Espiritu et al. [22] to transform the original configuration into a functionally equivalent series-parallel system. Since there are two load blocks in each configuration, the unavailabilities for the load blocks in the same configuration are not independent from each other. Therefore, we use Bayes' Theorem to calculate the conditional probability of not being able to serve energy to the second load block in the configuration given that we can/cannot serve energy to the first load block in the configuration. Therefore, it is possible to represent the distribution system by considering equivalent distribution lines from area grid to load block with the calculated unavailabilities.

There is also a similar natural gas network as in Zerriffi et al. [17] providing natural gas to these load blocks. The transmission pipelines are used to transmit natural gas from storage areas to 13 city-gates. Each city-gate has three sub-transmission mains, each of which feeds seven micro-grids. The distribution pipelines are used to distribute natural gas from city-gate to sub-transmission mains. The overall topology for the system can be seen in Fig. 2.

3. Monte Carlo simulation

We used simulation to represent the stochastic nature of the problem. Numerous scenarios were generated considering the availability of the system components. Each scenario represents a random hour of consumer demand and asset availability. The load duration curve is divided into segments, and then, demand is randomly chosen from the load duration curve for each segment. Monte Carlo simulation is used to randomly assign whether the system assets (lines, generation units, etc.) are available for that

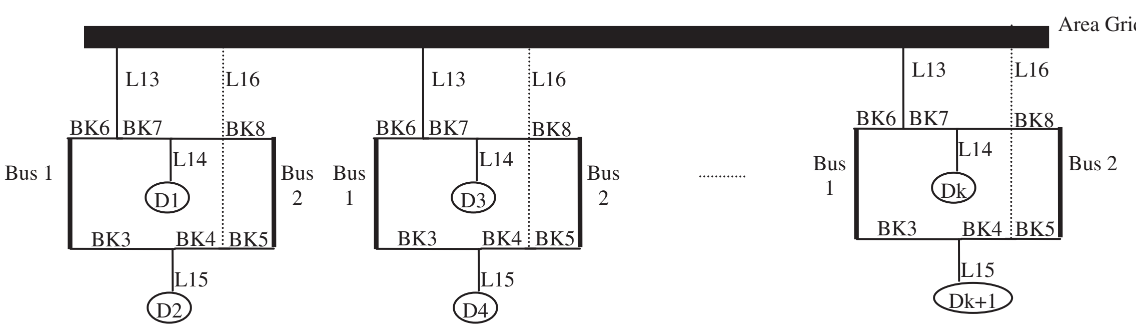

Fig. 1. Breaker-and-a half configuration-two diameters (L: Line, BK: Breaker, D: Demand Point).

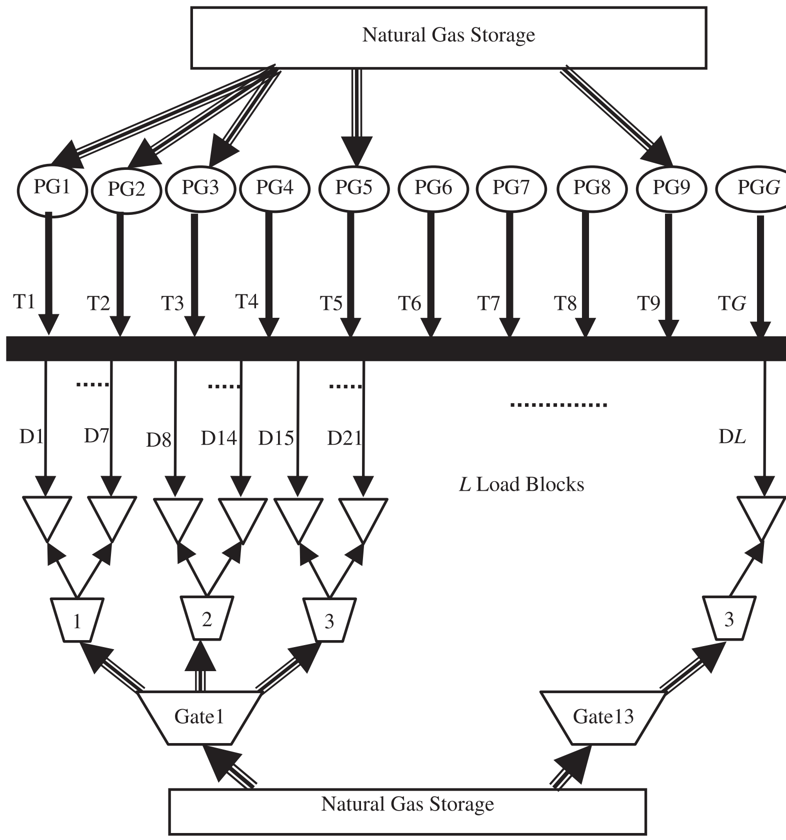

Fig. 2. The network topology.

scenario based on estimated component availability. As the planning horizon is extended, the demand increases for each year in the model. The demand increases for each year are applied by annually increasing the peak load demand.

The system components whose failures are considered are generation units, transmission lines, distribution lines, transmission pipelines providing natural gas to centralized units, transmission pipelines providing natural gas to city gates, and sub-transmission pipelines delivering natural gas to sub-mains. If these components fail, they are not available for that scenario. It is assumed that the backbone of the transmission and distribution grids and the micro-grids, which transfer natural gas from sub-transmission mains to local load blocks, are always available, similar to Zerriffi et al. [17].

Some of the parameters used in the mathematical model are scenario-based, and they are obtained from Monte Carlo simulation. More detailed explanation about the Monte Carlo Simulation and these parameters can be found in Tekiner et al. [23,24]. The parameters and their definitions are presented below.

- *Satisfiable demand in each scenario n in each time period t* (Ψ_{tn}). This represents the total demand which is calculated by summation of the local block demands which have the connection to the area grid in the corresponding scenario.
- *Locally satisfiable demand in each scenario n in each time period t for each load block l* (Φ_{tnl}).This is the demand at the load block where a distributed generation unit can be located and have no connection to the area grid in the corresponding scenario.
- *Available capacity of central unit k in each scenario n in each time period t* (γ_{tnk}). This is the available capacity of central units which is calculated based on the availability of the unit itself, availability of the natural supply (if it uses it as fuel), and the availability of transmission lines from the power group which the unit is located in the corresponding scenario.
- *Available capacity of distributed unit which can be used to meet satisfiable demand* (W_{tnlj}), and *available capacity of distributed unit which can be used to satisfy only local demand* (F_{tnlj}) *in each scenario*, *in each time period for each load block*. These are the available capacities of the distributed units which are calculated based on the availability of the unit itself, availability of the natural gas supply (if it uses it as fuel) and availability of the distribution network.

Scenarios are generated so that they have the same probability. Therefore, the probability for each scenario is calculated by dividing the probability of demand segment by the number of availability scenarios generated for the corresponding demand interval. The higher the demand level, the more availability scenarios are generated. Then, an adjustment factor, ϖ_n, which is the number of hours represented by each scenario n is calculated by multiplying the probability of each scenario by the total number of hours in the time period, which they represent.

4. Integration of Smart Grid technologies

There are many technological developments often called Smart Grid technologies, to improve the reliability and the efficiency of the energy distribution system. The purpose of this study is to investigate how these technologies, available to enhance the distribution system, affect the expansion plan. Therefore, a generation expansion problem is solved separately for different cases. Each case represents a system with different level of impact due to the Smart Grid technologies available.

As mentioned before, the stochastic nature of the network due to the unplanned outages is modeled by generating scenarios. Scenarios are generated by using Monte Carlo simulation based on the unavailability of the system components. To investigate the impact of the Smart Grid technologies, the effective unavailability of the components in the distribution system are decreased accordingly when Smart Grid technologies are adapted and the corresponding unavailabilities for the equivalent distribution lines from area grid to the load blocks are used as input for Monte Carlo simulation to generate scenarios for each case.

The availability of the system is affected by two things: the rate of failure and the rate of repair. Smart Grid technologies available for the distribution system are intelligent electronic devices, two-way communication system, remotely controllable distribution breakers and reclosers, distribution protective relays, automated switchers, etc. to provide reduction in the service time. Since the real-time system status is available, the fault and its location can be detected and remedied in a reduced time. Furthermore, since some devices such as automated switches installed along feeders and at feeder tie-points can be programmed to respond appropriately to fault conditions, the service time can be reduced. In addition, these technologies also decrease the failure rate. Since the real-time data about the condition of the system component is available, it is possible to perform condition-based maintenance, which decreases the number of outages. Moreover, technologies such as remotely controllable switches to backup devices can be used to anticipate and prevent failure of the component before it happens.

There are also a group of technologies that affect the demand. Some of them are used to shift the demand from peak hours to off-peak hours, and other technologies are used to decrease the energy demand. Some technologies such as energy storage devices are programmed to store energy during the off-peak hours and then provide this energy to use during on-peak hours which result in less energy demand from the grid. Other technologies such as smart thermostat and smart appliances communicate with the grid and work based on the grid condition. Furthermore, there are technologies which allow consumers to be more involved and choose the usage of energy based on the real time data of the grid. These technologies include advanced smart meters, demand responds programs, etc. When these technologies are available, the power grid can be operated more efficiently and expansion decisions will become different.

Based on the availability of the Smart Grid technologies for demand shifting, each case has different demand-shifting level. The demand level chosen for the segments representing the peak hours are reduced by the corresponding demand-shifting level, and demand level chosen for the segments representing the off-peak hours are increased. The necessary adjustments are done to make sure that total increase is equal to total decrease.

5. Model formulation

The objective is to find the expansion plan which simultaneously minimizes the cost and minimizes the air emissions. We used a weighted sum approach to solve the problem. The single objectives are scaled and combined into a single objective function. The weights to combine the individual objective functions are systematically varied to determine a Pareto set of non-dominated solutions, or a Pareto front. Once a Pareto set has been determined, there are methods to select a final subset of the most promising solutions. This is often referred to as "pruning" of the Pareto set. This can be an important first step to provide to the decision-makers a smaller set and the final decision can be made by considering both quantitative and non-quantitative criteria. Two common methods to select a most promising subset include prioritized objective functions (Taboada et al. [25], Taboada and Coit [26], Kulterel-Konak et al. [27]) and clustering of solutions (Taboada et al. [25]), Taboada and Coit [28]). Once the Pareto set has been pruned, decision-makers can select the particular solution to implement. If there is not a consensus or obvious solution to implement, then the Analytic Hierarchy Process (AHP) [29] is recommended to select a final solution among a selected subset of promising solutions. AHP is a structured technique for making complex decisions and selection of a best alternative.

The costs in our model consists of (i) investment cost, (ii) fixed operational and maintenance cost, (iii) electricity generation cost, (iv) unmet demand cost and (v) revenue from the steam generated. We consider two air emissions; CO_2 and NO_x. Since SO_2 and CO_2 emissions are highly correlated, by minimizing CO_2 we also minimize SO_2 emissions implicitly.

5.1. Investment cost

$$O_{11} = \sum_{t=1}^{T}(1+r)^{-t}\sum_{q=1}^{Q}s_{tq}a_{tq} + \sum_{t=1}^{T}(1+r)^{-t}\sum_{l\in\Lambda}\sum_{j=1}^{J_l}w_{tlj}b_{tlj} \tag{1}$$

s_{tq} is the investment decision of a central unit type q in time period t. That is, s_{tq} is equal to 1 if central unit type q is built in time period t and 0 otherwise. w_{tlj} is the investment decision of a distributed unit j located at load block l in time period t. That is, w_{tlj} is equal to 1 if distributed unit type j is built at load block l in time period t and 0 otherwise. a_{tq} is the investment cost ($) of a central unit type q in time period t, while b_{tlj} is the investment cost ($) of a distributed unit type j located at load block l in time period t. Here, r is the interest rate, T is the total number of time periods, Q is the total number of centralized generation investment options, Λ is the set of local load blocks in which distributed generation investment is possible, and J_l is the total number of distributed generation investment options available at local load block l.

5.2. Fixed operational and maintenance cost

$$O_{12} = \sum_{t=1}^{T}(1+r)^{-t}\sum_{k=1}^{K}g_{tk} + \sum_{t=1}^{T}(1+r)^{-t}\sum_{q=1}^{Q}\left(\sum_{\tau=1}^{t}s_{\tau q}\right)h_{tq} + \sum_{t=1}^{T}(1+r)^{-t}\sum_{l\in\Lambda}\sum_{j=1}^{J_l}\left(\sum_{\tau=1}^{t}w_{\tau lj}\right)m_{tlj} \tag{2}$$

g_{tk}, h_{tq} and m_{tlj} are the fixed operational and maintenance cost ($) for a existing central unit type k, new central unit type q and distributed unit type j located at load block l in time period t respectively. K represents the total number of centralized generation units existing in the system.

5.3. Generation cost

$$O_{13} = \sum_{t=1}^{T}(1+r)^{-t}\sum_{n=1}^{N}\sum_{k=1}^{K}\varpi_n x_{tnk}c_{tk} + \sum_{t=1}^{T}(1+r)^{-t}\sum_{n=1}^{N}\sum_{q=1}^{Q}\varpi_n u_{tnq}e_{tq} + \sum_{t=1}^{T}(1+r)^{-t}\sum_{n=1}^{N}\sum_{l\in\Lambda}\sum_{j=1}^{J_l}\varpi_n(y_{tnlj}+z_{tnlj})d_{tj} \tag{3}$$

x_{tnk} is the generation amount (MW) of existing central unit type k for scenario n in time period t. u_{tnq} is the generation amount (MW) of new central unit type q for scenario n in time period t. y_{tnlj} is the generation amount (MW) of distributed unit type j located at load block l to satisfy satisfiable demand. z_{tnlj} is the generation amount (MW) of distributed unit type j located at load block l to satisfy local demand. c_{tk}, e_{tq} and d_{tj} are the generation cost ($/MW) of existing central unit type k, new central unit type q and distributed unit type j in time period t respectively. The adjustment factor, ϖ_n is defined as the number of hours represented by each scenario n and N represent the total number of scenarios.

5.4. Unmet demand cost

$$O_{14} = \sum_{t=1}^{T}(1+r)^{-t}\sum_{n=1}^{N}\varpi_n \upsilon_{tn} f_t + \sum_{t=1}^{T}(1+r)^{-t}\sum_{n=1}^{N}\sum_{l\in\Lambda}\varpi_n \pi_{tnl} f_t \tag{4}$$

υ_{tn} and π_{tnl} are the unmet satisfiable demand (MW) for scenario n in time period t and unmet local demand at load block l for scenario n in time period t respectively. f_t is the cost of not satisfying the demand in time period t (\$/MW).

5.5. Revenue from steam

$$O_{15} = \sum_{t=1}^{T}(1+r)^{-t}\sum_{n=1}^{N}\sum_{l\in\Lambda}\sum_{j\in R}\varpi_n (y_{tnlj} + z_{tnlj}) p_t r_t \tag{5}$$

R is the set of distributed generation units with co-generation capabilities. p_t is the proportion of generated energy can be sold to receive cost benefit and r_t is the revenue obtained from the usage of steam (\$/MW).

5.6. Total cost

$$O_1 = O_{11} + O_{12} + O_{13} + O_{14} - O_{15} \tag{6}$$

5.7. CO_2 emission

$$O_2 = \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{k=1}^{K}\omega_n x_{tnk} C_{tk} + \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{q=1}^{Q}\varpi_n u_{tnq} E_{tq} + \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{l\in\Lambda}\sum_{j=1}^{J_l}\omega_n (y_{tnlj} + z_{tnlj}) D_{tj} \tag{7}$$

C_{tk}, E_{tq} and D_{tj} are the amounts (lbs) of CO_2 per MW generated by existing central unit type k, new central unit type q and distributed unit type j in time period t respectively.

5.8. NO_x emission

$$O_3 = \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{k=1}^{K}\omega_n x_{tnk} F_{tk} + \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{q=1}^{Q}\omega_n u_{tnq} G_{tq} + \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{l\in\Lambda}\sum_{j=1}^{J_l}\omega_n (y_{tnlj} + z_{tnlj}) H_{tj} \tag{8}$$

F_{tk}, G_{tq} and H_{tj} are the amounts (lbs) of NO_x per MW generated by existing central unit type k, new central unit type q and distributed unit type j in time period t respectively.

The mathematical model is as follows.

$$\min \quad z = w_1\overline{O}_1 + w_2\overline{O}_2 + w_3\overline{O}_3$$

$$s.t. \sum_{k=1}^{K} x_{tnk} + \sum_{q=1}^{Q} u_{tnq} + \sum_{l\in\Lambda}\sum_{j=1}^{J_l} y_{tnlj} + \upsilon_{tn} \geqslant \Psi_{tn} \quad \forall t,n \tag{9}$$

$$\sum_{j=1}^{J_l} z_{tnlj} + \pi_{tnl} \geqslant \Phi_{tnl} \quad \forall t,n,\forall l\in\Lambda \tag{10}$$

$$x_{tnk} \leqslant \gamma_{tnk} \quad \forall t,n,k \tag{11}$$

$$u_{tnq} \leqslant \gamma_{tnq}\sum_{\tau=1}^{t} s_{\tau q} \quad \forall t,n,q \tag{12}$$

$$y_{tnlj} \leqslant W_{tnlj}\sum_{\tau=1}^{t} w_{\tau lj} \quad \forall t,n,\forall l\in\Lambda,\forall j\in J_l \tag{13}$$

$$z_{tnlj} \leqslant F_{tnlj}\sum_{\tau=1}^{t} w_{\tau lj} \quad \forall t,n,\forall l\in\Lambda,\forall j\in J_l \tag{14}$$

$$\sum_{t=1}^{T} s_{tq} = 1 \quad \forall q \tag{15}$$

$$\sum_{t=1}^{T} w_{tlj} = 1 \quad \forall l\in\Lambda,\forall j\in J_l \tag{16}$$

$$s_{tq}\in\{0,1\} \quad \forall t,q \tag{17}$$

$$w_{tlj}\in\{0,1\} \quad \forall t,\forall l\in\Lambda,\forall j\in J_l \tag{18}$$

$$x_{tnk} \geqslant 0 \quad \forall t,n,k \tag{19}$$

$$u_{tnq} \geqslant 0 \quad \forall t,n,q \tag{20}$$

$$y_{tnlj} \geqslant 0 \quad \forall t,n,\forall l\in\Lambda,\forall j\in J_l \tag{21}$$

$$z_{tnlj} \geqslant 0 \quad \forall t,n,\forall l\in\Lambda,\forall j\in J_l \tag{22}$$

$$\upsilon_{tn} \geqslant 0 \quad \forall t,n \tag{23}$$

$$\pi_{tnl} \geqslant 0 \quad \forall t,n,\forall l\in\Lambda \tag{24}$$

The objective function is the summation of three scaled objectives ($\overline{O}_1, \overline{O}_2, \overline{O}_3$). The objective functions are linearly scaled between 0 and 1 by initially selecting a minimum and maximum value.

The first set of constraints is for satisfiable demand constraints. For each scenario and time period, the total generation and unmet demand should be at least as much as the satisfiable demand for corresponding scenario. The second set of constraints is for locally satisfiable demand. If the hypothetical distributed line for the load block has failed, then we can only satisfy the demand from distributed units located in that load block. Therefore, for those local load blocks where distributed units can be located, the total generation from distributed units and unmet local demand should be at least as much as local demand in that load block for each scenario. The third set of constraints restricts that the generation from existing central generation units to be smaller than the available generation capacity for each scenario. For the new central generation units, the generation should be smaller than the available capacity multiplied by the corresponding investment decision (0 or 1) for each scenario. We can use distributed generation units for satisfiable demand or locally satisfiable demand. The fifth set of constraints states that the generation from distributed generation unit to meet the satisfiable demand must be smaller than the available capacity of the distributed generation units for satisfiable demand multiplied by the corresponding investment decision for each scenario. The sixth set of constraints represents the generation from distributed generation unit to meet the local demand should be smaller than the available capacity of the distributed generation units for local demand multiplied by the corresponding investment decision for each scenario. The seventh and eighth sets of constraints are for expansion for each investment choice. We can only build each investment choice once over the planning horizon. The 9th and 10th set of constraints shows that the expansion decisions are binary variables, while the remaining constraints are nonnegativity constraints on dispatching decisions.

In this paper, different cases are defined by considering the different levels of the integration of Smart Grid technologies which have different impacts on the system. For each case, the impacts of available Smart Grid technologies on the power system are defined and scenarios are generated by considering these impacts. Then, the model presented in this section is solved to find the expansion plans and to investigate how the expansion plans changes according to the presence of the Smart Grid technologies.

6. Numerical examples and discussions

To demonstrate the model, an example problem is solved for a 15 year planning horizon. In the example system, there are 50 load

Table 1
Demand segments and corresponding probabilities, number of scenarios and adjustment factors.

Demand segments in terms of % of peak load demand	Segment Prob.	# of Scenarios	Adjustment factor	Demand intervals in terms of % of peak load	Interval Prob.	# of Scenarios	Adjustment factor
1.00	0.01	20	4.38	(0.60,0.70)	0.23	10	201.48
(0.95,0.99)	0.01	15	5.84	(0.50,0.60)	0.21	5	367.92
(0.90,0.95)	0.02	15	11.68	(0.40,0.50)	0.22	5	385.44
(0.80,0.90)	0.11	15	64.24	(0.33,0.40)	0.03	5	52.56
(0.70,0.80)	0.16	10	140.16				

blocks where the distributed units can be located. The planning horizon is divided into three time periods of 5 years each. Therefore, if a new generation unit is to be installed, the options are to install it as soon as possible, in 5 years, or in 10 years for the current period. Since each time period represents 5 years, the cost parameters for fixed O&M cost are also adjusted accordingly. In each year there are 100 different demand and availability scenarios that are randomly generated to reflect the range of possible failure and/or outage conditions. Therefore, the optimization is based on a total of 1500 different scenarios.

The existing network has 32 generation units consisting of consisting of Oil/combustion turbine (CT), Oil/Steam, Coal/Steam, combined cycle gas turbine (CCGT) and nuclear. Total existing capacity is 3405 MW. These generation units are distributed among 10 power groups. Some of the generation units use natural gas as fuel. The existing generation units with corresponding capacity, unavailability, fixed operation and maintenance cost, variable cost, CO_2, NO_x and SO_2 emissions can be found in Tekiner et al. [23,24]. The gas emissions characteristics used are obtained from New Jersey Draft Energy Master Plan Modeling Report [30] and the cost and availability characteristics are obtained from Zerriffi et al. [17]. There are 273 independent local load blocks and these load blocks are connected to the area grid by the equivalent distribution lines.

Internal combustion (IC) engines are considered as distributed generation units. The engines use natural gas as fuel and have co-generation capabilities. In order to minimize the binary decision variables, 25 engines are assumed to be built together and the capacity of the distributed generation can be considered as binomial random variables. Their capacity, unavailability, cost characteristics, and gas emissions can be found in Tekiner et al. [23,24].

The technologies available to add to power groups are Oil/Steam (197 MW), Coal/Steam (155 MW), Wind Turbines (50 MW), Nuclear (400 MW), Combined Cycle Gas Turbines (CCGT/76 MW). We assume that 30% of wind generation capacity can be used to generate electricity [31]. In this study, we assume that the system has sufficient transmission line capacity. However, installation of wind turbines may require adding new transmission lines to the system. As a result, we increase the capital investment cost for the wind turbine by 30%. The corresponding capacity, unavailability, investment cost, fixed operation and maintenance cost, variable cost, gas emissions can be found in Tekiner et al. [23,24].

We divide the load duration curve into nine segments. In our example, the first three segments represent the peak demand hours where demand is reduced by effective Smart Grid technologies and the segment 7 and 8 represent the off-peak demand hours where the demand is increased if possible. Table 1 presents the demand segments, corresponding probabilities, number of scenarios generated, and adjustment factors.

The peak load demand in this problem is 2850 MW and we also assume that demand increases 1% in each year. The cost of not satisfying demand is estimated as 10,000 $/MW. We also consider that 50% of energy produced by distributed generation units can be used to gain benefits from the steam, and in our model, the profit per MW by using steam is approximately 60% of energy generation cost from IC, i.e., 15.91 $/MW. The unavailabilities for the transmission lines are estimated to be 0.01. The unavailability for the natural gas transmission pipelines and sub-transmission pipelines are 9.5×10^{-5} and 9.5×10^{-6}, as in Zerriffi et al. [17].

We use 26 different weight combinations are considered as presented in Table 2 to study different preferences for cost and air emission minimization. Also, we assume that only one nuclear power plant can be built over the 15 year planning horizon. In the first weight combination, the objective is only to minimize cost.

6.1. Generation expansion plans for networks with/without Smart Grid technologies affecting demand

We define three cases to investigate the changes in the expansion plans based on the existence of Smart Grid technologies which can shift the demand. In these cases, the unavailability of the components in the distribution configuration is estimated to be 0.005. In the first case, we consider the power grid which does not have any Smart Grid technologies which can shift the demand. In the second and third case, the power grid is assumed to have such technologies. The difference between the Cases 2 and 3, the demand shift impact of the existing Smart Grid technologies is different. Proposed cases are:

Case 1: No demand shift.
Case 2:

- Demand levels selected for scenarios in the segment 1–3 are reduced by 5%. Consider that R is the total demand reduction.
- Demand level selected for a scenario in the segment 7 and 8 is increased by $(R/\varpi_7 + \varpi_8)$ where ϖ_7, ϖ_8 are the adjustment factors for the scenarios in segment 7 and 8 respectively.
- Demand levels selected for scenarios in other segments remain the same.

Case 3:

- Demand levels selected for scenarios in the segment 1–3 are reduced by 10%. Consider that R is the total demand reduction.
- Demand level selected for a scenario in the segment 7and 8 is increased by $(R/\varpi_7 + \varpi_8)$.
- Demand levels selected for scenarios in other segments remain the same.

The objective function values for the set of non-dominated or Pareto solutions, i.e., a Pareto front, for three cases are presented in Table 3 and the corresponding expansion plans are presented in Table 4. In the tables we present the expansion plans, D stands for distributed generation units, C for CCGT, W for wind turbines and N for nuclear plants. The expansion plans and dispatching changes based on the relative importance of the objective functions. Here, we first present the general observation valid for all cases according to the different weight combinations, and then, we present comparison between the cases.

The main reason for unmet demand is having no operational connection from area grid to load block. Therefore, in most weight

Table 2
Weight combinations.

#	Cost	CO_2	NO_x	#	Cost	CO_2	NO_x	#	Cost	CO_2	NO_x	#	Cost	CO_2	NO_x	#	Cost	CO_2	NO_x
2	0.9	0.1	0	7	0.8	0.2	0	12	0.7	0.3	0	17	0.6	0.4	0	22	0.5	0.5	0
3	0.9	0.075	0.025	8	0.8	0.15	0.05	13	0.7	0.225	0.075	18	0.6	0.3	0.1	23	0.5	0.375	0.125
4	0.9	0.05	0.05	9	0.8	0.1	0.1	14	0.7	0.15	0.15	19	0.6	0.2	0.2	24	0.5	0.25	0.25
5	0.9	0.025	0.075	10	0.8	0.05	0.15	15	0.7	0.075	0.225	20	0.6	0.1	0.3	25	0.5	0.125	0.375
6	0.9	0	0.1	11	0.8	0	0.2	16	0.7	0	0.3	21	0.6	0	0.4	26	0.5	0	0.5

Table 3
Objective function solutions for Pareto-front for Cases 1, 2 and 3.

Weight Comb.	Cost is in millions dollars and gas emissions are in thousands of tons											
	Case 1				Case 2 (5% demand shift)				Case 3 (10% demand shift)			
	Cost	CO_2	NO_x	SO_2	Cost	CO_2	NO_x	SO_2	Cost	CO_2	NO_x	SO_2
1	26,629	125,304	251	819	26,592	125,510	251	821	26,551	124,802	244	820
2	27,784	75,406	127	371	27,760	75,388	126	372	27,729	74,988	123	373
3-4	27,744	76,055	115	382	27,723	75,980	115	382	27,699	75,473	114	381
5-6	27,561	79,475	117	385	27,545	79,295	117	385	27,520	78,821	116	384
7	28,642	63,241	172	157	28,649	62,949	172	153	28,659	62,110	173	145
8	28,504	64,990	79	235	28,505	64,698	78	231	28,482	63,949	77	226
9-10-11	28,965	60,572	61	137	28,968	60,264	60	133	28,940	59,471	58	128
12	29,302	56,079	109	70	29,301	55,803	108	67	29,280	55,038	105	63
13-14	29,436	56,376	48	95	29,436	56,073	48	91	29,405	55,173	46	86
15-16	29,598	55,294	45	84	29,597	54,996	45	81	29,405	55,173	46	86
17	32,600	34,848	67	41	32,603	34,473	66	38	32,433	34,736	71	40
18	32,812	34,911	29	55	32,774	34,701	29	54	32,779	33,965	27	48
19-20-21	29,760	54,352	43	75	29,759	54,059	42	72	29,729	53,289	41	68
22	34,679	27,435	50	30	34,680	27,048	48	28	34,548	26,909	49	28
23-24	33,106	33,809	26	45	33,110	33,419	25	42	32,904	33,504	26	44
25-26	29,760	54,352	43	75	29,759	54,059	42	72	29,729	53,289	41	68

Table 4
Expansion plans for Cases 1, 2 and 3.

Weight Comb.	Number of generation technologies added to the system																	
	Case 1						Case 2 (5% demand shift)						Case 3 (10% demand shift)					
	T1				T2		T1				T2		T1				T2	
	D	C	W	N	D	C	D	C	W	N	D	C	D	C	W	N	D	C
1	41				7		41				6		41				6	
2	49				1		49				1		44				4	
3-4	49				1		49				1		44				4	
5-6	49				1		49				1		44				4	
7	50	2					50	2					50	2				
8	49	4			1		49	4			1		44	4			4	
9-10-11	49	5			1		49	5			1		44	5			4	
12	50	6					50	6					50	6				
13-14	49	8			1		49	8			1		44	8			4	
15-16	49	9			1		49	9			1		44	8			4	
17	50	4		1			50	4		1			50	3		1		
18	49	6		1	1		49	5		1	1	1	44	6		1	4	
19-20-21	49	10			1		49	10			1		44	10			4	
22	50	3	10	1		1	50	3	10	1		1	50	3	10	1		
23-24	49	7		1	1	1	49	7		1	1	1	44	6		1	4	1
25-26	49	10			1		49	10			1		44	10			4	

combinations, almost all the distributed generation (DG) units are built to minimize unmet demand. Besides, building distributed generation units is cost beneficial, assuming that there is a buyer for their steam at the equivalent of 15.91 $/MW. Since in this example, distributed generation units are using natural gas, they are also environmental friendly compared to coal and oil.

There are some common results for all cases which are impacted based on the relative importance of the three objective functions. As the table indicates, for the first combination which is to find the least cost expansion plan, there is no central unit investment. This is because the existing reserve of the system with newly built distributed generation is high enough to cover the expected demand. When the weight for cost is decreased, the expansion decisions changes towards environmental friendly technologies. CCGTs (combined cycle gas turbines) are introduced to the system even when the weight of the cost is decreased by 0.2. When only CO_2 is considered, CCGTs are introduced into the system to reduce the production mainly from coal burning units. When NO_x is introduced to the objective, more CCGTs are constructed also to reduce the production from Oil/CT and IC engines for satisfiable demand. For the combinations where the cost has relatively high priority, the reduction on emissions is done by

Table 5
Objective function solutions for Pareto-front for Cases 4, 5 and 6.

Weight Comb.	Cost is in millions dollars and gas emissions are in thousands of tons										
	Case 4				Case 5				Case 6			
	Cost	CO_2	NO_x	SO_2	Cost	CO_2	NO_x	SO_2	Cost	CO_2	NO_x	SO_2
1	22,435	124,394	246	815	16,710	124,913	249	813	16,344	125,331	252	813
2	23,645	72,297	115	341	17,903	74,033	120	355	17,560	73,189	116	344
3	23,621	72,724	106	348	17,887	74,436	110	362	17,549	73,535	107	349
4	23,621	72,724	106	348	17,922	73,514	107	349	17,549	73,535	107	349
5	23,440	75,689	103	326	17,672	78,183	110	353	17,299	78,201	110	353
6	23,462	75,132	100	314	17,759	76,202	101	316	17,385	76,220	101	316
7	24,343	61,125	149	152	18,486	64,222	148	194	18,083	64,441	147	199
8	24,138	63,886	77	230	18,580	63,417	74	215	18,205	63,438	74	215
9-10	24,586	59,520	59	134	18,855	61,065	62	144	18,480	61,085	62	144
11	24,586	59,519	59	134	19,004	59,424	57	127	18,629	59,444	57	127
12	24,880	55,492	103	75	19,257	56,328	94	84	18,863	56,436	93	85
13-14	25,049	55,253	47	92	19,428	55,790	47	91	19,052	55,809	47	91
15-16	25,052	55,232	47	91	19,470	55,510	46	88	19,094	55,528	46	88
17	28,181	34,338	64	44	22,536	35,823	60	51	22,145	35,894	60	52
18	28,369	34,325	29	55	22,664	35,803	30	59	22,289	35,818	30	59
19-20-21	25,374	53,298	41	72	19,633	54,532	43	78	19,258	54,551	43	78
22	30,094	27,537	47	33	24,411	29,141	41	35	24,022	29,187	41	35
23-24	28,707	33,058	25	44	23,010	34,470	26	46	22,634	34,484	26	46
25-26	25,374	53,298	41	72	19,633	54,532	43	78	19,258	54,551	43	78

Table 6
Expansion plans for Cases 4, 5 and 6.

Weight Comb.	Number of generation technologies added to the system																						
	Case 4									Case 5							Case 6						
	T1				T2		T3			T1				T2		T3	T1				T2		T3
	D	C	W	N	D	C	D	C	O	D	C	W	N	D	C	D	D	C	W	N	D	C	D
1	39				1				1	37							37						
2	44							2		37					1		35	1					
3	43				1			2		37					1		35	1					
4	43				1			2		36	1						35	1					
5	39				5			1		36	1						35	1					
6	39	1			5	1				30	2			3			30	2			3		
7	44	1								36	3						35	3					
8	38	3			5		1			30	5			1		2	30	5			1		2
9-10	38	4			5		1			30	5			1		2	30	5			1		2
11	37	5			5		1			30	6			1		2	30	6			1		2
12	44	5								36	7						35	7					
13-14	37	6			5		1			30	8			1	1	2	30	8			1	1	2
15-16	37	8			5		1			30	9			1		1	30	9			1		1
17	44	8		1						36	4		1		1		35	4		1		1	
18	37	4		1	5	1	1			30	6		1	1		1	30	6		1	1		1
19-20-21	37	5			5		1			30	10			1		1	30	10			1		1
22	44	10	9	1						36	5	8	1		1		35	5	8	1		1	
23-24	37	4		1	5	1	1			30	8		1	1		1	30	8		1	1		1
25-26	37	7			5		1			30	10			1		1	30	10			1		1

CCGTs. When the weight of the cost reaches its lowest levels, wind turbines and nuclear plants are also included in the expansion plan to reduce CO_2 emission.

The availability of Smart Grid can have a very meaningful and significant impact. The expansion plan for Case 3 differs from the one for Case 1 for almost all weight combinations which clearly demonstrates both the benefits from Smart Grid technologies, but also that the presence of Smart Grid technologies impacts power grid expansion decisions. For the first weight combination, one less DG units is constructed. For the second combination and all the others where the weight of NO_x is higher than zero, two less DG unit are constructed and the construction of three DG units are postponed from time period 1 to time period 2. For the combinations 15-16-17-22-23-24, one less CCGT is constructed in Case 3. The improvement in objective functions is higher, and in all combinations, the cost and CO_2 emissions are improved. This means that the demand which was met by using the generation technologies with relatively higher variable cost and CO_2 emission during the peak hours, is now being met by the technologies with lower variable cost and CO_2 emission during the off-peak hours. NO_x emission is also improved for the most combinations, except the one where the weight of NO_x is zero.

The expansion plan for Case 2 differs from the one for Case 1 for two weight combinations, numbers 1 and 18 which shows that even though the impact of the Smart Grid technologies is relatively low, the expansion plan can differ. Although, the expansion plan did not change as much between Cases 2 and 1, the objective function values are improved. Since the peak demand is shifted to off-peak hours, it is possible to use preferable generation technologies to cover this shifted amount. Based on the weight combinations, preferable generation technology may differ, i.e., for the first combination the preferable generation technologies are the ones with less variable cost, for the weight combination 26, preferable generation technologies are the one with less NO_x emissions and

Table 7
Objective function solutions for Pareto-front for Cases 7, 8, 9 and 10.

Weight Comb.	Cost is in millions of dollars and gas emissions are in thousands of tons															
	Case 7				Case 8				Case 9				Case 10			
	Cost	CO_2	NO_x	SO_2	Cost	CO_2	NO_x	SO_2	Cost	CO_2	NO_x	SO_2	Cost	CO_2	NO_x	SO_2
1	22,176	125,228	247	821	17,019	126,362	247	825	17,155	124,793	246	808	16,979	123,296	243	808
2	23,385	75,147	124	374	18,263	77,492	129	389	18,342	73,309	113	336	18,240	69,665	104	311
3	23,358	75,637	114	382	18,236	77,982	118	397	18,331	73,596	105	341	18,320	67,139	89	279
4	23,358	75,637	114	382	18,236	77,982	118	397	18,331	73,596	105	341	18,320	67,139	89	279
5	23,174	79,057	117	385	18,080	80,884	120	400	18,090	78,093	108	345	18,024	72,458	90	271
6	23,174	79,057	117	385	18,080	80,884	120	400	18,179	76,017	99	306	18,045	71,957	87	261
7	24,167	63,613	169	173	19,216	63,445	157	159	18,814	65,128	151	196	18,797	58,603	115	140
8	24,106	64,355	78	231	19,200	63,986	73	210	18,954	64,106	74	214	18,779	59,424	64	174
9	24,567	59,856	59	132	19,483	61,571	61	137	19,236	61,700	62	141	19,004	57,502	54	116
10	24,567	59,856	59	132	19,483	61,571	61	137	19,236	61,700	62	141	19,043	57,058	53	112
11	24,567	59,856	59	132	19,483	61,571	61	137	19,388	60,002	57	124	19,045	57,030	53	111
12	24,881	55,716	104	72	19,913	56,219	95	68	19,606	56,910	94	82	19,255	54,323	84	75
13-14	25,032	55,553	47	90	20,062	56,160	45	83	19,857	55,980	45	84	19,345	54,498	45	86
15	25,032	55,553	47	90	20,062	56,160	45	83	19,857	55,980	45	84	19,345	54,498	45	86
16	25,032	55,553	47	90	20,103	55,886	45	81	19,857	55,980	45	84	19,345	54,498	45	86
17	28,197	34,324	65	41	23,213	35,145	59	39	22,955	35,727	56	48	22,561	33,474	54	44
18	28,419	34,196	28	52	23,291	35,600	29	54	23,078	35,825	29	56	22,672	33,557	27	51
19-20-21	25,357	53,648	41	71	20,265	54,951	42	72	20,020	55,025	43	75	19,671	52,671	40	69
22	30,307	26,819	45	29	25,217	27,896	47	30	25,068	28,264	42	35	24,487	26,749	38	31
23-24	28,711	33,073	25	41	23,626	34,291	25	41	23,371	34,686	26	45	22,965	32,474	24	41
25-26	25,357	53,648	41	71	20,265	54,951	42	72	20,020	55,025	43	75	19,671	52,671	40	69

less cost. Therefore, for most weight combinations, the cost is improved. For some of them, a small increase in cost occurs to get more benefit in the gas emissions. In all weight combinations, the CO_2 and NO_x emissions are improved, except the first one, which is to minimize the cost. Therefore, the shifted amount is met by using the generation units with less cost, which have higher gas emissions. This shows that, if the objective is only to minimize the cost, there actually can have a negative impact on the environment.

6.2. Generation expansion plans for networks with/without Smart Grid Technologies affecting component availability

We define four cases to investigate the changes in the expansion plans based on the existence of Smart Grid technologies which can improve the availability of the component in the distribution system. For these cases, we assumed that there is no demand shifting available. In Case 1, the grid is considered to have no Smart Grid technologies which improve the availability of the distribution system components. In Cases 4, 5 and 6, it is considered that the power grid has such technologies, but in different levels of penetration. Proposed cases as follows:

Case 1: The unavailability of the distribution system components is 0.005.
Case 4: The unavailability of the distribution system components is 0.001.
Case 5: The unavailability of the distribution system components is 0.0005.
Case 6: The unavailability of the distribution system components is 0.0001.

The objective function values of the solutions within the Pareto front for the Cases 4, 5 and 6 are presented in Table 5 and the corresponding expansion plans are presented in Table 6. As stated previously, the main reason for unmet demand is the unavailability of the distribution system. Therefore, for the cases with higher availabilities, the distribution system is more reliable. This means that unmet demand due to the distribution system failure will be lower, which decreases the cost. Furthermore, since the distribution system is more reliable, fewer distributed generation units are built or their investment times are postponed. As an illustration, for the weight combinations 19-20-21; the expansion plan for Case 1 includes 49 DG units in time period 1; however, for Case 6, in which the unit availabilities are the highest, only 30 DG units are built in time period 1, one more is added in time period 2 and another one is constructed in time period 3. For some weight combinations, more CCGTs are constructed to reduce the generation from mainly coal burning units since less distributed generation units are constructed in those cases. The objective function values are also improved. For example, the cost is 27% less in Case 6 than it is in Case 4.

6.3. Generation expansion plans for networks with/without Smart Grid technologies affecting demand and component availability

In order to see the combined effects of Smart Grid technologies, we define six cases to investigate the changes in the expansion plans based on the existence of Smart Grid technologies which can improve the availability of the component in the distribution system or/and shift the demand. In Case 1, the grid is considered to have no Smart Grid technologies which improve the availability of the distribution system components and no demand shifting. In Case 7, the grid has Smart Grid technologies which can improve the availability of the distribution system components from 0.005 to 0.001 and shift the demand by 5%. In Case 8, the effect on the availability is the same as in Case 7, but the demand can be shifted by 10%. In Case 4, the system is considered to have only Smart Grid technologies which can improve the availabilities from 0.005 to 0.001. In Case 9, the grid is considered to have technologies improving the availabilities from 0.005 to 0.0001 and shifting the demand by 5%. In Case 10, the impact on availabilities is the same, but the demand can be shifted by 10%. Proposed cases as follows:

- *Case 1*: The unavailability of the distribution system components is assumed to be 0.005 and no demand shifting
- *Case 7*: The unavailability of the distribution system components is assumed to be 0.001 and 5% demand shifting.
- *Case 8*: The unavailability of the distribution system components is assumed to be 0.001 and 10% demand shifting.

Table 8
Expansion plans for Cases 7, 8, 9 and 10.

Weight Comb.	The number of generation technologies added to the system																											
	Case 7							Case 8							Case 9							Case 10						
	T1				T2		T3	T1				T2		T3	T1				T2		T3	T1				T2	T3	
	D	C	W	N	D	C	D	D	C	W	N	D	C	D	D	C	W	N	D	C	D	D	C	W	N	C	D	C
1	30				7			23				9		2	25				25			48						
2	*40*				*3*		*1*	*37*				*4*		*2*	*32*	*2*			*6*	*2*		*42*	*1*					*1*
3	*40*				*3*		*1*	*36*				*5*		*2*	*32*	*2*			*6*	*2*		*35*	*2*					*1*
4	*40*				*3*		*1*	*36*				*5*		*2*	*32*	*2*			*6*	*2*		*35*	*2*					*1*
5	*40*				*3*		*1*	*36*				*5*		*2*	*32*	*2*			*6*	*2*		*35*	*2*					*2*
6	*40*				*3*		*1*	*36*				*5*		*2*	*32*	*3*			*1*	*2*	*1*	*35*	*2*					*3*
7	44	2						43	3						35	3						34	3			2		1
8	39	4			3		1	35	5			5		2	32	5					1	33	5			1	1	
9	39	5			3		1	35	5			5		2	32	5					1	33	5			1	1	
10	39	5			3		1	35	5			5		2	32	5					1	33	6				1	
11	39	5			3		1	35	6			5		1	32	6					1	33	6				1	
12	*45*	*6*						*43*	*7*						*35*	*7*						*35*	*7*					
13-14	*39*	*8*			*3*		*1*	*35*	*8*			*5*	*1*	*1*	*32*	*9*					*1*	*31*	*8*				*1*	
15	*39*	*8*			*3*		*1*	*35*	*8*			*5*	*1*	*1*	*32*	*9*					*1*	*31*	*8*				*1*	
16	*39*	*8*			*3*		*1*	*35*	*9*			*5*		*1*	*32*	*9*					*1*	*31*	*8*				*1*	
17	45	4		1				43	4		1		1		35	5		1				35	4		1	1		
18	39	6		1	3		1	35	5		1	5	1	1	32	6		1			1	31	5		1	1	1	
19-20-21	39	10			3		1	35	10			5		1	32	10					1	31	10				1	
22	*44*	*4*	*10*	*1*				*44*	*3*	*10*	*1*		*1*		*35*	*5*	*10*	*1*		*1*		*35*	*4*	*9*	*1*	*1*		
23-24	*39*	*7*		*1*	*3*	*1*	*1*	*35*	*7*		*1*	*5*	*1*	*1*	*32*	*8*		*1*		*1*	*1*	*31*	*6*		*1*	*2*	*1*	
25-26	*39*	*10*			*3*		*1*	*35*	*10*			*5*		*1*	*32*	*10*					*1*	*31*	*10*				*1*	

Table 9
The percentage improvement between Cases 1 and 10.

Weight Comb.	Cost	CO_2	NO_x	SO_2	Weight Comb.	Cost	CO_2	NO_x	SO_2
1	36.24	1.60	3.19	1.34	12	34.29	3.13	22.94	−7.14
2	34.35	7.61	18.11	16.17	13-14	34.28	3.33	6.25	9.47
3	33.97	11.72	22.61	26.96	15	34.64	1.44	0.00	−2.38
4	33.97	11.72	22.61	26.96	16	34.64	1.44	0.00	−2.38
5	34.60	8.83	23.08	29.61	17	30.79	3.94	19.40	−7.32
6	34.53	9.46	25.64	32.21	18	30.90	3.88	6.90	7.27
7	34.37	7.33	33.14	10.83	19-20-21	33.90	3.09	6.98	8.00
8	34.12	8.56	18.99	25.96	22	29.39	2.50	24.00	−3.33
9	34.39	5.07	11.48	15.33	23-24	30.63	3.95	7.69	8.89
10	34.26	5.80	13.11	18.25	25-26	33.90	3.09	6.98	8.00
11	34.25	5.85	13.11	18.98	12	34.29	3.13	22.94	−7.14

- *Case 4*: The unavailability of the distribution system components is assumed to be 0.001 and no demand shifting.
- *Case 9*: The unavailability of the distribution system components is assumed to be 0.0001 and 5% demand shifting.
- *Case 10*: The unavailability of the distribution system components is assumed to be 0.0001 and 10% demand shifting.

The objective function values of solutions in the Pareto front for these four cases are presented in Table 7 and the corresponding expansion plans are presented in Table 8. The expansion plans and the objective function values differ for each case. In order to provide a better insight how the Smart Grid technologies are affecting the operation of the system and the expansion plan, we compare the two extreme cases: Cases 1 and 10. All the objective functions are improved in all weight combinations. Since the availability of the distribution system is increased, there is less unmet demand which results in less cost. Although the system generates more energy to meet the demand, it is observed that the gas emissions are also improved in Case 10 compared to Case 1. This is because of two things; the better distribution system and demand shift. Due to the better distribution system, it is possible to meet the local demand by using more environmentally friendly generation units such as nuclear power plants, and CCGTs, instead of using distributed generation units which has relatively higher CO_2 emissions. Due to the demand shift, there is an increased flexibility to choose generation technologies which improve our objectives. This means that the shifted demand can be met by using more environmentally friendly generation technologies. The percentage improvements are given in Table 9.

7. Conclusion

In this study, we investigate how the expansion plans are changing under different weight combinations of objective functions and different cases according to the existence of the Smart Grid technologies in the system. This study shows that the objective functions can be improved if there are Smart Grid technologies available in the system. However, this analysis did not consider the cost of these technologies. Therefore, it is also necessary to compare the benefits of Smart Grid technologies to the cost of having these technologies available in order to determine if the technologies are net beneficial. We mainly focus on the technologies which affects the availability of the distribution system component and the demand. Other types of technologies which affect the availability of the central generation units, transmission lines or natural gas supplies can also be investigated with the proposed method.

The Smart Grid technologies affecting the availabilities reduce the operational cost by reducing the unmet demand cost and by making it possible to utilize least cost generation units. They also decrease the gas emissions by making it possible to satisfy local demand by the central generation units with lower gas emissions. In addition, the Smart Grid technologies shifting the demand reduce the operational costs by enabling to use the least cost generation units to satisfy the shifted demand or reduce the gas emissions by enabling to use generation units with lower gas emissions to satisfy the shifted demand. Since the grid is designed to satisfy the peak load demand, fewer generation units are introduced in the presence of Smart Grid technologies.

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