A Framework for Expansion Planning of Data Centers in Electricity and Data Networks under Uncertainty

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***Abstract*— This paper presents the expansion planning for data centers and data routes in the data and electricity networks considering the uncertainties in the planning horizon to ensure an acceptable rate of service to the requests received from the end-users in the data network. The objective is to determine the location and capacity of the data centers as well as the required data routes while considering the imposed constraints in the electricity and data networks. The installation cost of data centers and data routes, as well as the expected operation cost of the data centers, are minimized. The proposed problem addressed the uncertainties in the expansion planning of the electricity networks including the availability of renewable generation resources, the variations in electricity demand, the availability of generation and transmission components in the electricity network and the uncertainties in the number of requests received by the user groups (UGs) in the data network. The problem is formulated as a mixed integer linear programming problem and Bender decomposition and electricity price signals are used to capture the interaction among the data and electricity networks. The presented case study shows the effectiveness of the proposed approach.**

***Index Terms*— Data center, expansion planning, data route, Benders decomposition**

NOMENCLATURE

Indices:

a, b	Index of bus
d	Index of loads other than data centers
e	Type of data route
i	Index of data center
j, r	Index of UG
l	Index of transmission line
n	Type of data center module
p	Index of time interval within a year
s	Index of scenario
w	Index of wind unit
y, y'	Index of year
φ	Index of thermal unit

Integer variables:

$m_{i,n}^{p,y,s}$	Number of active servers in a data center module of type n
$\lambda_{j,i,n}^{p,y,s}$	Rate of the requests directed by UG j to data center module of type n [request/second]
$\lambda'^{p,y,s}_{r,j}$	Rate of the requests exchanged among the UGs [request/second]

Binary variables:

$k_{i,n}^{y}$	Decision variable for installing data center module of type n
$h_{i,n}^{y}$	Auxiliary variable for installing data center module of type n
$R_{(.),(.)}^{y,e}$	Decision variable for installing data route of type e

Real variables:

$F_c(.)$	Generation cost function
$P_{\varphi}^{p,y,s}$	Generation dispatch of thermal generation unit [MW]
$PL_l^{p,y,s}$	Power flow of line l [MW]
$P_w^{p,y,s}$	Generation dispatch of wind unit [MW]
$t_{1,(.)}^{(.)}, t_{2,(.)}^{(.)}$	Slack variables
$\tau_{(.)}^{(.)}, \delta_{(.)}^{(.)}$	Lagrange multipliers
$\theta_b^{p,y,s}$	Voltage angle of bus

Parameters:

D	Desired response time [millisecond]
d_y	Annual discount rate
$\hat{k}_{(.)}^{(.)}$	Decision made in the master problem for installing a data center module

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$L_j^{p,y,s}$	The rate of requests received by the UG [request/second]
$L_{f,b}, L_{t,b}$	Set of lines starting from/ending at bus b
M_n	Maximum number of servers in data center module of type n
$\hat{m}_{(.)}^{(.)}$	Number of active servers determined in the master problem
N_e	Capacity of the data route [request/second] of type e
NT	Total number of hours in a period
P_{idle}, P_{peak}	Power consumption of server in idle and active modes [W]
$P_d^{p,y,s}$	Demand of consumers other than data centers in the electricity network [MW]
$P_w^{f,p,y}$	Forecasted dispatch of wind unit [MW]
$P_\varphi^{\max}$	Maximum generation dispatch of thermal generation unit [MW]
$q_{(.),(.)}$	Distance [mile]
$U_{(.)}^{(.)}$	Availability of the electricity network components; 1 for being available and 0 otherwise
$X_{b,a}$	Inductance of line between buses a and b
β_n	Installation cost of data center module type n [\$]
γ_e	Installation cost of data route type e [\$/mile]
$\psi_{(.)}^b$	Set of components connected to bus b
μ	Rate of request processed by each server [request/second]
ρ^s	Probability of scenario
$\hat{\lambda}$	Decision made in the master problem
$\hat{\delta}_b^{p,y,s}$	Price of electricity [\$/MWh]

I. INTRODUCTION

INTERNET Data Centers (IDCs) are the physical layouts of the computing clouds that are equipped with thousands of devices including switches, routers and several types of servers to provide various services to the end-users [1]. Considering the massive scale of IDCs, a considerable amount of energy is consumed by these entities that needs to be considered in the electricity network operation planning. In 2011, the energy consumption of IDCs was approximately 1.5% of the total electricity consumption worldwide and was increased by 56% from 2005-2010 [2]. The challenges associated with the reliability and economics of energy supply for the IDCs are further highlighted with the increasing proliferation of cloud computing. Energy-related costs are estimated as 46% of the operation cost of an IDC [3]. Energy management solutions such as energy efficiency in chip multiprocessing [4], network power management [5], online control for power supply system [6], and storage power management [7] are among the major efforts to conserve energy in the IDCs. Virtual machine (VM) live migration technology [8] enables spatial shifting of workloads among servers through multiple VM deployments. Consequently, IDCs are envisioned as large and flexible electrical loads that facilitate demand response practices to reduce the total peak demand by up to 20% [9]-[14]. The study in [15] investigates the potential benefits of flexible IDC power management utilizing local fuel cell generation. Other studies investigated the benefit of spatial shifting the workloads of the data centers to the locations with cheaper energy or abundant renewable resources [16], [17]. There are generally two categories of workloads: delay-intolerant and delay-tolerant workloads. Delay-intolerant workloads such as web searches and web services have limited flexibility in temporal shifting whereas the delay-tolerant workloads such as CPU-intense batch computing jobs are shiftable to the periods in which the energy is cheaper [18]-[20]. Furthermore, load shedding considering the required Quality-of-Service (QoS) can reduce the energy consumption and associated costs [21]. The researcher work reported in [22]-[25] examined the coordinated operation of data centers and renewable resources to minimize the carbon footprint and the operation cost. The expansion planning of data centers in electricity and data networks was addressed in [26]. Here, the objective was to find a deterministic solution for the expansion planning while the operation cost of the data centers, as well as the uncertainty in the planning horizon were ignored.

While the earlier research is focused on developing approaches to address the operation schedule of the IDCs in the electricity market, there are limited research efforts dedicated to the expansion planning of the IDCs in the electricity and data networks. The IDC expansion planning reported in [27] addresses the capacity allocation of the future site constructions/expansion of data centers to meet the demand in the data network. Such practice is important as the future data centers are expected to be established in areas with lower electricity prices, least cost for data routes and bandwidth capacity, and lower carbon footprint and environmental effects. The outdated data centers, insufficient capacity of current data centers, the adventure of big data, virtualization and new applications outsourced to cloud services highlight the merit of the expansion planning for the IDCs [28]. Such expansion planning strategies are further underlined as the traditional perceptions of IDC facilities – that were low-density and site-constructed, with considerable planning lead time – were transformed toward flexible, more rapidly deployable and modular assets.

Expanding the IDC capacity as new demand entity in the electricity network that operates close to its capacity limits, will reduce the reliability and security of energy supply [29]. Hence, the capacity expansion strategies for IDCs should capture the reliability and security of energy supply as the quality of service provided by the IDCs to the cloud users, is affected by the quality of utilized energy.

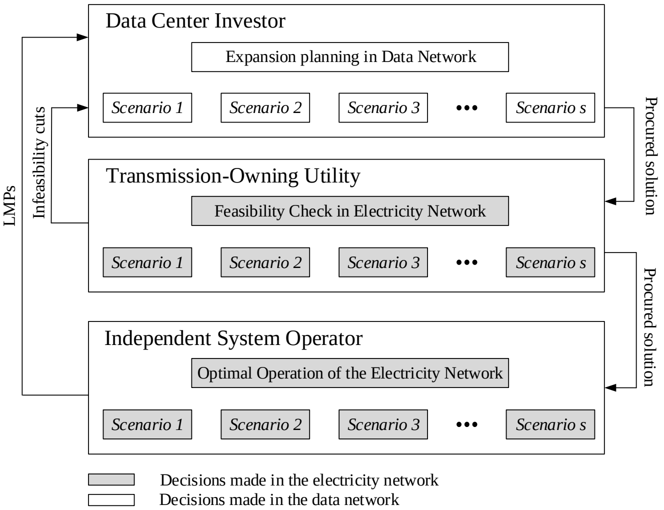

Fig. 1. The proposed framework for the IDC expansion-planning in electricity and data networks

This paper presents a coordinated expansion planning for the IDCs and data routes considering the operation cost of the IDC and the security of energy supply in the electricity network. The presented research is focused on the economic aspects of the expansion planning of IDCs in the data and electricity networks while ensuring the energy supply security. The proposed expansion strategies determine the location and capacity of the IDCs and the required data routes among the User Groups (UGs) and IDCs while ensuring the security of energy supply. The presented coordination between the electricity and data networks ensures the adequacy and reliability of energy supply for the IDCs. The unavailability of the generation and transmission assets, as well as transmission congestions in the electricity network, would impact the expansion planning strategies for IDCs in the data network.

The proposed expansion-planning framework captures the uncertainties in the electricity and data networks including the variation in demand, the volatility of renewable energy resources, the outages in generation and transmission components, and the fluctuation in the number of requests received by the UGs. Several scenarios capture the uncertainty in the planning horizon. Fig. 1 shows the proposed expansion-planning framework. As the figure illustrates, the Data Center Investor (DCI) procures the expansion plan for the IDCs and corresponding data routes in the data network. The feasibility of such decisions in the electricity network is evaluated by one or multiple transmission-owning utilities (TOUs). The DCI who manages and invests on the IDCs determines the decisions to install the IDC modules and data routes by solving a mixed integer programming (MIP) problem (master problem) that captures the uncertainty in the data network. Such decisions are passed to the TOUs to check for the feasibility of the network considering the demand of proposed IDCs in multiple scenarios (feasibility sub-problems). If any infeasibility exists in each scenario, infeasibility cuts are generated and sent back to the master problem. In other words, the DCI sends the decisions on installing the IDCs with respective electricity loads to the TOU(s). The TOU(s) may accept the proposed installation or propose different suggestion in case there is a deficiency in the energy supply. In this paper, the TOUs send capacity signals to the DCI for revising the proposed expansion plan to satisfy the TOUs' constraints [30]. The Benders cuts received from the TOUs are essentially the infeasibility cuts that reflect the feasibility of the expansion decisions made by the DCI. Once the decisions are feasible, the network operation problem in multiple scenarios is solved by the Independent System Operator (ISO) considering the imposed demand by the IDCs. As a result, the location marginal prices (LMPs) of electricity are passed to the DCI to determine the operation cost of the IDCs in different scenarios and to update the expansion decisions if required. This iterative process stops once the expansion decisions are feasible and certain stopping criteria for the operation cost are satisfied. It worth noting that formulating the problem as one optimization problem solved by system operators or DCI is not practically feasible. The system operators in the electricity network (TOU and ISO) neither handle the expansion planning practices for the data centers nor do have any information on the demand of the data network such as the rate of requests received and re-directed by the UGs. Furthermore, DCIs have limited access to the information on the electricity network to determine the feasibility of the IDC expansion plans. This paper proposed a framework to capture the interactions among DCI and system operators (TOU and ISO) for the expansion planning of the data centers in the electricity and data network.

The rest of the paper is organized as follows: Section II describes the problem formulation and solution methodology. Sections III and IV present the case study and conclusion, respectively.

II. PROBLEM FORMULATION

The IDC expansion problem provides solutions for increasing the capacity of the IDCs and data routes to serve the customer demand in the data network. Each IDC module consists of several types of servers including web servers, application servers, and database servers. The type of requests determines the characteristics of the workloads and the loading pattern of the corresponding servers [31]. For the sake of simplicity in this paper, all requests are considered to be of

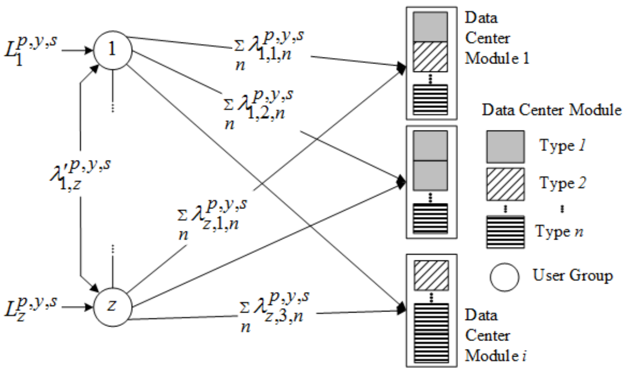

Fig. 2. Modular structure of data centers with USGs, and data routes.

the same type and the workload is dependent on the number of requests received. The UGs aggregate the end-user requests, communicate with the IDCs and send the outcomes back to the end users. The UG – also known as load balancer among a group of backend servers – aggregate the requests received from the end-users, re-distribute the incoming traffic among backend servers in the IDCs, and send the processed requests back to the end-users [27], [32]. UGs are linked together by the data routes for load balancing, sharing the requests and distribute the workloads among the IDCs.

In the proposed problem, DCI invests on expanding and allocating the IDC module and data route capacity to ensure the quality of service in the data network. The capacity of the IDC is determined by the number of installed modules on an annual basis [33]. The growth in the electricity demand and the number of requests in the data network are captured in the planning horizon. Fig. 2 shows the structure of the data network in the proposed problem. The figure shows that there are z UGs, each receiving the total input request rate, $L_j^{p,y,s}$, from the end-users in scenario s. The UGs communicate with three IDCs. Data center i, $i \in \{1,2,3\}$ receives requests from the UG_j with the rate of $\sum_n \lambda_{j,i,n}^{p,y,s}$ and the rate of exchanged requests among UG_j and UG_r is $\lambda_{j,r}'^{p,y,s}$. Data routes leverage fiber optics technology to facilitate fast and reliable communication among the UGs and IDCs. The bandwidth of the data route that connects the UGs to the IDC is determined based on the rate of the directed requests. The number of servers that process the data is dependent on the rate of requests received from the UGs. The queueing model *M/M/1*, with Poisson arrival rate, is used to obtain the average response time. As shown in (1), the average response time captures the average waiting time of requests in the queue and the process time of the IDC. Here, D is the desired response time for the end-users; P_Q is the probability of waiting in the queue, and $P_Q = 1$ once the large volume of data is being processed by the IDCs [34].

$$P_Q \big/ (m_{i,n}^{p,y,s}\mu - \lambda_{j,i,n}^{p,y,s}) \le D \tag{1}$$

The expansion-planning problem for DCI is an MIP problem that minimizes the expansion and expected operation costs of the IDC and data routes. In this problem, the binary variables are the decisions made to install the IDCs and data routes in the data networks, the integer variables are the number of servers that process the requests in each scenario. Such decisions are made based on the requested data demands by UGs in each scenario. In order to ensure the energy supply security for IDCs in the electricity network, DCI interacts with one or multiple TOUs to ensure the adequacy of energy supply for the installed IDCs. For the sake of simplicity in this paper, one TOU interacts with the DCI and Benders decomposition is used to capture such interactions. The TOU checks for the security of the electricity network in each scenario considering the imposed demand for the IDC. If the decisions made by the DCI do not ensure the energy security, the TOU sends the capacity signal in form of Benders cut to change the DCI decisions until the energy supply security is guaranteed. If the decisions made by the DCI ensures the energy security in the electricity network, the ISO solves the economic dispatch to procure the LMPs in each scenario. The LMP of electricity is used by the DCI to assess the expected operation cost of the IDCs and to update the expansion decisions accordingly. In the following sections, the application of Benders decomposition for solving this problem is described and the solution framework to solve the proposed coordinated expansion problem is presented.

A. Application of Benders Decomposition

The general form of the presented expansion planning problem is formulated in (2)-(6) as an MIP problem where $\mathbf{x}$ is the vector of integer and continuous variables and $\mathbf{y}$ is the vector of binary variables, respectively. Here, $f(.)$ represents the expected operation cost of the IDCs and $h(.)$ is the installation cost of the IDCs and data routes. The constraints that capture the feasibility of the decisions in the electricity network are shown in (4)-(5) where, $\mathbf{v}$ is the continuous decision variable for the electricity network.

$$\min f(\mathbf{x}) + h(\mathbf{y}) \tag{2}$$

s.t.

$$\mathbf{Ax} + \mathbf{By} \ge \mathbf{c} \tag{3}$$

$$\mathbf{Gx} + \mathbf{Hv} = \mathbf{d} \tag{4}$$

$$\mathbf{Kv} \le \mathbf{w} \tag{5}$$

$$\mathbf{x} \ge \mathbf{0}, \mathbf{y} \in \{0,1\}, \mathbf{v} \in \Omega_v \tag{6}$$

The problem (2)-(6) is decomposed into a master problem (7)-(10) and sub-problem (11)-(14).

$$\min z \tag{7}$$

s.t.

$$z \ge f(\mathbf{x}) + h(\mathbf{y}) \tag{8}$$

$$\mathbf{Ax} + \mathbf{By} \ge \mathbf{c} \tag{9}$$

$$\mathbf{x} \ge \mathbf{0}, \mathbf{y} \in \{0,1\} \tag{10}$$

In the master problem (7)-(10), the upper bound of the objective function is minimized as shown by (8). The decision variables $\mathbf{x}$ and $\mathbf{y}$ are determined by the DCI once (7)-(10) is solved [30]. The set of equality and inequality constraints shown in (9) captures the physical relationship among the decision variables in the data network. The feasibility of the decision variables in (7)-(10) is checked in (11)-(14). Here, the violation in (4) as a result of determined decision $\hat{\mathbf{x}}$ in (7)-(10), is minimized. In order to check the violation of the equality constraint (4), the vector of slack variables $\mathbf{t}$ (i.e. mismatch variables) is minimized. In this formulation, the set of constraints (12) and (13) captures the physical relationship among the decision variables in the electricity network and these constraints are not shared with the DCI. Therefore, (11)-(14) is solved by the TOU and if the objective function (11) is zero, the proposed DCI solution is feasible in the electricity network. Otherwise, Benders cut (15) will be passed to the master problem (7)-(10). In the next sections, the general formulation that is described above will be formulated for the proposed expansion planning problem.

$$\min U(\hat{\mathbf{x}}) = \mathbf{1}^T \mathbf{t} \tag{11}$$

s.t.

$$\mathbf{G}\hat{\mathbf{x}} + \mathbf{H}\mathbf{v} + \mathbf{I}\mathbf{t} = \mathbf{d} \qquad (\boldsymbol{\tau}) \tag{12}$$

$$\mathbf{K}\mathbf{v} \le \mathbf{w} \tag{13}$$

$$\mathbf{t} \ge \mathbf{0} \tag{14}$$

$$U(\hat{\mathbf{x}}) + (\mathbf{x} - \hat{\mathbf{x}})^T \mathbf{G}^T \boldsymbol{\tau} \le 0 \tag{15}$$

B. *Master Problem – Expansion planning in data networks*

The problem formulation for the coordinated expansion planning of the IDC and data route is shown in (16)-(25). The vectors of binary, integer and continuous variables are $\mathbf{y} = [\mathbf{k}, \mathbf{R}]$, $\mathbf{x} = [\mathbf{m}, \boldsymbol{\lambda}]$ where $R_{j,r}^{y,e} \in \mathbf{R}$, $k_{i,n}^{y} \in \mathbf{k}$, $m_{i,n}^{p,y,s} \in \mathbf{m}$ and $\lambda_{j,i,n}^{p,y,s} \in \boldsymbol{\lambda}$. The objective is to minimize the upper bound of the installation cost of IDCs and data routes as well as the expected operation cost of the IDCs, as shown in (17). The first term in (17) is the installation cost of the IDC modules as well as the capital cost of the data routes that are installed between the UGs and the IDCs; the second term reflects the installation cost of data routes installed between the UGs and the third term is the expected operation cost of IDCs in which $\hat{\delta}_b^{p,y,s}$ is the LMP of electricity. Here, the rate of requests that is received or processed is associated with the utilized electricity in the IDC and the presented formulation captures a snapshot for each period. As shown in the last term in (17), the total energy consumed by servers in each period to process the requests with given rates, is determined by the power consumption of the servers and the length of the period (*NT*). The number of active servers at each period in each scenario, is lower than the installed capacity as shown in (18). The number of requests exchanged between the UGs and IDCs in each scenario is limited by the installed capacity of the data routes as shown in (19). Similarly, the number of requests exchanged between the UGs in each scenario is limited by the installed capacity of the data routes as shown in (20).

$$\min\ Z \tag{16}$$

s.t.

$$\begin{aligned} Z \ge \sum_{y}\sum_{i} &\left\{ \begin{aligned} &\left(\left(1+d_y\right)^{1-y} \cdot \sum_{n}\left(\beta_n \cdot k_{i,n}^{y}\right) \right) \\ &+ \left(\left(1+d_y\right)^{1-y} \cdot \sum_{j} q_{j,i} \cdot \sum_{e} \gamma_e \cdot R_{j,i}^{y,e} \right) \end{aligned} \right\} \\ &+ \sum_{y} \left\{ \left(1+d_y\right)^{1-y} \cdot \sum_{j,j\ne r} \sum_{r} \frac{1}{2} q_{j,r} \cdot \sum_{e} \gamma_e \cdot R_{j,r}^{y,e} \right\} + \\ &\sum_{s} \rho^s \cdot \sum_{i \in \psi_i^b} NT \cdot \sum_{p}\sum_{y} \left\{ \left[\left(1+d_y\right)^{1-y} \cdot \hat{\delta}_b^{p,y,s} \right] \cdot \left[\begin{aligned} &\left(\sum_{n} m_{i,n}^{p,y,s} \cdot \left[P_{idle} + P_{peak} \right] \right) \\ &+ \left(P_{peak} - P_{idle} \right) \cdot \mu^{-1} \cdot \sum_{j}\sum_{n} \lambda_{j,i,n}^{p,y,s} \end{aligned} \right] \right\} \end{aligned} \tag{17}$$

$$m_{i,n}^{p,y,s} \le \sum_{y'=1}^{y} M_n \cdot k_{i,n}^{y'} \tag{18}$$

$$\sum_{n} \lambda_{j,i,n}^{p,y,s} \le \sum_{y'=1}^{y} \sum_{e} N_e \cdot R_{j,i}^{y',e} \tag{19}$$

$$\left| \lambda_{r,j}'^{\,p,y,s} \right| \le \sum_{y'=1}^{y} \sum_{e} N_e \cdot R_{j,r}^{y',e} \qquad r \ne j \tag{20}$$

$$R_{j,r}^{y,e} = R_{r,j}^{y,e} \tag{21}$$

$$m_{i,n}^{p,y,s} \ge \left(\mu^{-1} \cdot \sum_{j} \lambda_{j,i,n}^{p,y,s} \right) + \left(D.\mu\right)^{-1} \cdot h_{i,n}^{y} \tag{22}$$

$$h_{i,n}^{y} \ge Q^{-1} \cdot \sum_{y'=1}^{y} k_{i,n}^{y'} \tag{23}$$

$$L_j^{p,y,s} + \sum_{r,r\ne j} \lambda_{r,j}'^{\,p,y,s} = \sum_{i}\sum_{n} \lambda_{j,i,n}^{p,y,s} \tag{24}$$

$$\lambda_{r,j}'^{\,p,y,s} = -\lambda_{j,r}'^{\,p,y,s} \qquad r \ne j \tag{25}$$

Constraint (21) ensures the symmetry in the decisions to develop data route among UGs, *j* and *r*. The number of active servers in an IDC, to process the directed requests at each interval in each scenario is determined by (22). Here $h_{i,n}^{y}$ is a binary variable that is calculated in (23), and represents the installation status of IDC type n until year y. Since the number of active servers is limited by the capacity of the IDC, $h_{i,n}^{y}$ will be 1 if any IDC module is constructed until year *y* as shown by (23) and Q is a large scalar. The requests received by each UG in each scenario are equal to the requests that are transferred to the IDC and the requests that are transferred to other UGs as shown in (24). The requests exchanged between the UGs are directional, as shown in (25). The proposed master problem (16)-(25), is an MIP problem in which the binary variables represent the decisions on the installation of IDC modules and data routes, the integer variables determine the number of active servers to serve the customers' request, and the continuous variables represent the rate of requests processed by the IDC modules. The procured solution is passed to the feasibility check sub-problem as described in the next section.

C. *Electricity Network Security Check Sub-problem*

The network security check sub-problem is formulated as (26)-(32). The objective is to minimize the mismatch between the generation and demand for all buses at each period and scenario, considering the imposed electricity demand by the IDCs. The nodal power balance for each period and scenario in the electricity network is shown in (27). The generation dispatch of thermal and wind units in each period and scenario is limited to their capacity as shown in (28) and (29). The unavailability of generation unit is captured by a corresponding binary parameter representing the state of the unit. The dc power flow formulation in which the flow of the line is dependent on the difference between the voltage angles at the ends of the line is presented in (30). If a transmission line is unavailable ($U_l^{p,y,s} = 0$) the voltage angles at the ends of the line are relaxed. The flow of the line is further limited by (31). If there is a mismatch in (26), the positive slack variables will be non-zero and the infeasibility Benders cut (32) is generated and sent to the master problem (16)-(25). Here $\hat{W}^{p,y,s}$ is the value of the objective function. This iterative process continues until there is no violation in the sub-problem and the slack variables are zero.

$$\min W^{p,y,s}=\sum_{b}\left(t_{1,b}^{p,y,s}+t_{2,b}^{p,y,s}\right) \tag{26}$$

s.t.

$$\begin{aligned}&\sum_{\varphi\in\psi_{\varphi}^{b}}P_{\varphi}^{p,y,s}+\sum_{w\in\psi_{w}^{b}}P_{w}^{p,y,s}-\sum_{d\in\psi_{d}^{b}}P_{d}^{p,y,s}\\&-\sum_{i\in\psi_{i}^{b}}\left[\sum_{n}\hat{m}_{i,n}^{p,y,s}\cdot[P_{idle}+P_{peak}]+(P_{peak}-P_{idle})\cdot\mu^{-1}\cdot\sum_{j}\sum_{n}\hat{\lambda}_{j,i,n}^{p,y,s}\right]\qquad(\tau_{b}^{p,y,s})\\&+t_{1,b}^{p,y,s}-t_{2,b}^{p,y,s}=\left[\sum_{l\in L_{t,b}}PL_{l}^{p,y,s}-\sum_{l\in L_{f,b}}PL_{l}^{p,y,s}\right]\end{aligned} \tag{27}$$

$$0\le P_{\varphi}^{p,y,s}\le P_{\varphi}^{max}\cdot U_{\varphi}^{p,y,s} \tag{28}$$

$$0\le P_{w}^{p,y,s}\le P_{w}^{f,p,y}\cdot U_{w}^{p,y,s} \tag{29}$$

$$-Q\cdot(1-U_{l}^{p,y,s})\le X_{b,a}^{-1}\cdot\left[PL_{l}^{p,y,s}-\left(\theta_{b}^{p,y,s}-\theta_{a}^{p,y,s}\right)\right]\le Q\cdot(1-U_{l}^{p,y,s}) \tag{30}$$

$$\left|PL_{l}^{p,y,s}\right|\le PL_{l}^{\max}\cdot U_{l}^{p,y,s} \tag{31}$$

$$\hat{W}^{p,y,s}+\sum_{b}\sum_{i\in\psi_{i}^{b}}\tau_{b}^{p,y,s}\cdot\left[\begin{array}{l}(P_{peak}-P_{idle})\cdot\mu^{-1}\cdot\sum_{j}\sum_{n}(\lambda_{i,j,n}^{p,y,s}-\hat{\lambda}_{i,j,n}^{p,y,s})\cdot\\(P_{idle}+P_{peak})\cdot(\sum_{n}m_{i,n}^{p,y,s}-\hat{m}_{i,n}^{p,y,s})\end{array}\right]\le 0 \tag{32}$$

D. *ISO's Optimal Operation Problem*

Once the feasibility of the electricity network is ensured, the solution is passed to the ISO to determine the LMP of energy in the electricity network. This problem addresses the economic dispatch in the electricity network considering the imposed demand by the IDCs. The objective function is the operation cost of the generation units for each scenario as shown in (33) that is subjected to nodal generation and load balance (34), and other constraints of the electricity network (28)-(31). The Lagrange multiplier associated with nodal generation demand balance determines the LMP of electricity in each scenario as shown in (34).

$$\min[\sum_{s}\sum_{y}\sum_{p}\sum_{\varphi}F_{c}(P_{\varphi}^{p,y,s})] \tag{33}$$

s.t.

$$\begin{aligned}&\sum_{\varphi\in\psi_{\varphi}^{b}}P_{\varphi}^{p,y,s}+\sum_{w\in\psi_{w}^{b}}P_{w}^{p,y,s}-\sum_{d\in\psi_{d}^{b}}P_{d}^{p,y,s}\\&-\sum_{i\in\psi_{i}^{b}}\left[\begin{array}{l}\sum_{n}\hat{m}_{i,n}^{p,y,s}[P_{idle}+P_{peak}]+\\(P_{peak}-P_{idle})\cdot\mu^{-1}\cdot\sum_{j}\sum_{n}\hat{\lambda}_{j,i,n}^{p,y,s}\end{array}\right]\qquad(\delta_{b}^{p,y,s})\\&=\sum_{l\in L_{t,b}}PL_{l}^{p,y,s}-\sum_{l\in L_{f,b}}PL_{l}^{p,y,s}\end{aligned} \tag{34}$$

$$\left|1-Z^{new}/Z^{old}\right|\le\varepsilon \tag{35}$$

Once the LMPs of electricity are updated, the master problem in (17) is solved and the operation cost of the IDC and the decisions made in the master problem is updated accordingly. The updated solution of the master problem is passed to the security check sub-problem to check for the feasibility of the decisions in the electricity network. Similarly, the LMPs of electricity will be updated with the updated decisions for installing the IDCs in the master problem. This iterative process could stop once the sum of the investment and operation costs of the IDCs and data routes is not changing as shown in (35) where ε is a small scalar. If the process does not converge in practice, the number of iterations could be limited by the number of interactions among the ISO(s) and DCI.

III. CASE STUDY

In this section, a 6-bus power system and the IEEE 118-bus power system are used to evaluate the efficiency of the presented expansion-planning framework. The planning horizon is 20 years and the annual request growth rate in the data network is 10% [35]. The bandwidth of the fiber optics data routes is typically 1-6 Gbyte/sec. Here, only one type of data route with 4 Gbyte/sec bandwidths is considered [36], [37]. For the sake of simplicity, it is assumed that each request corresponds to 500 Kbps data transmission [38]. The cost of developing data routes to transmit 8,000 requests per second is 12,800 \$/mile [39]. The installation cost of an IDC depends on several factors including the available space, capacity, cooling and the leveraged network technologies [40]. The average idle power consumption for each server is 100W ($P_{idle}=100W$), the peak power consumption for a server is 200W ($P_{peak}=200W$) [41], and the number of hours in each period is 730. The expansion planning of IDC in the data network, the electricity network security check sub-problem, and the economic dispatch are solved using Gurobi 5.6. Scenario generation and reduction techniques to address the uncertainties are presented in the next section.

A. *Scenario generation and reduction*

The stochastic solution captures the uncertainties in the rate of requests in the data network, electricity demand, wind generation, and the outages in generation and transmission components in the power network. A large number of scenarios was generated using Monte-Carlo simulation and scenario reduction techniques were utilized to reduce the number of effective scenarios by eliminating the low probability scenarios and by bundling the comparable scenarios [43]. The forecast error in electricity demand and rate of requests for UGs are presented by Gaussian distribution function with the mean equal to the forecasted electrical demand and rate of request for UG in each period and the standard deviations equal to 3% of the mean values. The Weibull probability distribution function is used to represent the uncertainty in the wind speed [44],[45] and wind generation is determined using the wind speed and wind turbine speed-power curve [46]. In this case, the uncertainties are captured by generating 3,000 scenarios and scenario reduction techniques including fast backward method, fast backward/forward method, and fast backward/backward method can be used to reduce the number of effective scenarios [43], [47]. These methods have diverse computational performance, and the choice of approach depends on the size of the problem and the expected level of solution accuracy. The fast backward method provides the best computational performance with least accuracy for large scenario trees; however, the fast forward method procures more accurate results at the cost of longer computational time. In this paper, the fast backward/forward method is selected to reduce the number of scenarios to 13.

B. 6-bus Power System

Fig. 3 shows a sample 6-bus power system which represents the electricity network in this case. The characteristics of the generation units and transmission lines are shown in Tables I and II, respectively. Wind generation is located on bus 3. The annual demand growth in this network is 5%. The wind generation capacity is 18 MW. Here, the shape and scale parameter associated with Weibull distribution is set to 2.67 and 7.85, respectively [48]. The data network consists of two UGs that receive the requests from the end users. All buses in the electricity network were considered as candidates for installing IDC modules. Each server in an IDC will process 3 requests per second. Three types of IDC modules, k_1, k_2, and k_3, with 500, 1000, and 1500 servers were considered respectively. The total power consumption of a data center module type k_1, k_2, and k_3 considering full CPU utilization is 0.2, 0.4, and 0.6 MW and the installation cost is \$0.4M, \$0.64M, and \$0.96M respectively. The length of the data routes between the UGs and IDCs are presented in Table III. The distance between the UGs is 15 miles. The desired response time of IDCs to the received requests should not exceed 300 msec. For the sake of simplicity, the latency in data routes is ignored. The demand rate for the UGs in each period in the first year is shown in Table IV. The expansion planning is performed for 20 years and each year consists of 12 equal periods, each consists of 730 hours.

TABLE I
THERMAL UNITS CHARACTERISTICS

Unit	a (\$/MW^{2}h)	b (\$/MWh)	c (\$/h)	P_{max} (MW)
G1	0.79	6.6	1.4	40
G2	1.1	7.6	1.3	30
G3	2.5	10	1.1	20

The following four cases are considered:
Case 1 – Deterministic solution without congestion
Case 2 – Deterministic solution with congestion
Case 3 – Deterministic solution with outages
Case 4 – Stochastic solution

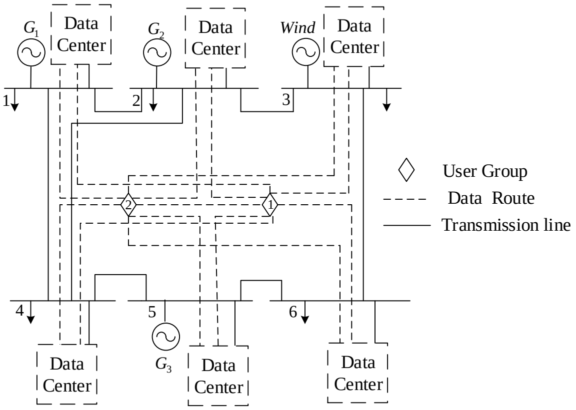

Fig. 3. A 6-bus power system with candidate IDCs and data routes

TABLE II
TRANSMISSION LINES CHARACTERISTICS

Line	From Bus	To Bus	Impedance (Ω)	Maximum Power Flow (MW)
1	1	2	0.17	26
2	1	4	0.258	32
3	2	4	0.197	16
4	5	6	0.14	16
5	3	6	0.018	30
6	2	3	0.037	36
7	4	5	0.037	26

TABLE III
DISTANCES OF UGS FROM BUSES IN MILES

	B1	B2	B3	B4	B5	B6
UG_1	35	22	23	35	27	21
UG_2	26	21	35	23	23	33

TABLE IV
RATE OF REQUESTS FOR UGS IN EACH PERIOD FOR THE FIRST YEAR

Period	1	2	3	4	5	6
UG_1	3914	5548	4698	6875	6770	7695
UG_2	4261	3701	4180	5063	7551	5822
Period	7	8	9	10	11	12
UG_1	9182	6024	3790	7698	3757	1947
UG_2	4156	2843	3775	7886	5806	5834

1) Case 1-Deterministic solution without congestion

Tables V and VI show the installation decisions for IDC modules and data routes, respectively. The IDC modules were built on buses 2, 3, 4, and 6. The total number of installed modules is 29; including 5, 15, and 9 modules of type k_1, k_2, and k_3 respectively. One data route was installed between the UGs in year 1.

As shown in Tables V and VI, buses that are closest to the UGs (i.e. buses 2, 3, and 6 that are close to UG_1, and buses 2 and 4 that are close to UG_2) were selected to install IDC modules. In year 1, the UGs are connected to exchange requests with each other. In period 4 of year 1, the rates of requests received by UG_1 and UG_2 are 6875, and 5063 requests per second respectively. In this period UG_1 passes 1753 requests per second to the UG_2, and UG_2 sends 6816 requests per second to the IDC at bus 4.

In years 3-5 modules of type k_2 are installed at bus 2 and the rate of requests transferred from UG_1 to UG_2 increased until year 6. By establishing modules of type k_2 at bus 6 in years 6-8, the exchange rate among the UGs decreases.

TABLE V
EXPANSION OF IDCS IN CASE 1

Year	1	2	3	4	5	6	7	8	9	10
Bus 2	-	k_3	k_2	k_2	k_2	k_2	k_2	k_2	k_2	k_2
Bus 3	k_3	k_1	-	-	-	-	-	-	-	-
Bus 4	k_3	k_1	-	-	-	-	-	-	-	-
Bus 6	k_1	k_1	-	-	-	k_2	k_2	k_2	-	-
Year	11	12	13	14	15	16	17	18	19	20
Bus 2	k_2	k_2	k_2	k_2	k_3	k_3	k_3	k_3	k_3	k_3
Bus 3	-	-	-	k_1	-	-	-	-	-	-

The total cost for DCI, in this case, is \$20.22M. The installation cost of IDC is \$8.92M and the installation cost of data routes (IDR) is \$1.93M, and the operational cost of data centers (OC) is \$9.37M. Establishing the link between the UGs will save \$470K in this case. In this case, the LMPs were

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updated 3 times by the ISO. The number of iterations for finding a feasible solution for the TOU in the first, second, and third iterations are 3, 1, and 1 respectively. The interaction between DCI and TOU is shown by measuring the mismatch in the objective function of the electricity network security-check sub-problem in Fig. 4. Here, as the mismatch in the objective function of the sub-problem reduces to zero, the procured DCI's solution will become feasible in the electricity network. As shown in this figure, for the first iteration of updating the LMPs, TOU can serve the IDC modules after sending Benders cuts in three iterations. The solution time for this case is 7207 seconds.

TABLE VI
EXPANSION OF DATA ROUTES IN CASE 1

Year	1	2	3	4	5	6	7	8	9	10
(UG_1, bus 2)	0	0	1	0	0	0	0	0	0	1
(UG_1, bus 3)	1	0	0	0	0	0	0	0	0	0
(UG_1, bus 6)	1	0	0	0	0	0	0	0	0	0
(UG_2, bus 2)	0	1	0	0	0	0	1	0	0	0
(UG_2, bus 4)	1	0	0	0	0	0	0	0	0	0
Year	11	12	13	14	15	16	17	18	19	20
(UG_1, bus 2)	0	0	1	0	0	0	0	1	0	1
(UG_2, bus 2)	0	0	0	0	1	0	1	0	0	0

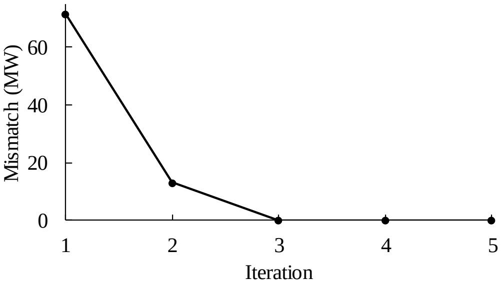

Fig. 4. Mismatch in the electricity network security-check sub-problem for the first iteration of updating the LMPs

2) *Case 2 – Deterministic solution with congestion*

In this case, the capacity of lines "1" and "5" are reduced to 12 and 19 MW, respectively, to evaluate the effect of congestion in the power system. As a result, line "1" and "5" are congested in years 15-20 and 17-20 respectively. The outcomes are shown in Tables VII and VIII. The total number of installed modules is 31; which includes 5, 22 and 4 modules of type k_1, k_2, and k_3, respectively. In this case buses 2, 3, 5, and 6 selected to install IDC modules. Comparing with Case 1, it is seen that the number of IDC modules installed at bus 3 and bus 2 was increased and decreased respectively. The total cost is increased by $890K, however, installing the IDC modules at bus 3 relieves the congestion on line 5 and reduces the operation cost of the DCI by $30K.

TABLE VII
EXPANSION OF IDCS IN CASE 2

Year	1	2	3	4	5	6	7	8	9	10
Bus 2	k_3	k_1	-	-	-	-	-	-	-	-
Bus 3	k_3	k_1	-	-	k_2	-	k_2	k_2	k_2	k_2
Bus 5	k_1	k_1	-	-	-	-	-	-	-	-
Bus 6	k_1	k_2	k_2	k_2	-	k_2	-	-	-	-
Year	11	12	13	14	15	16	17	18	19	20
Bus 2	-	-	-	-	-	-	-	k_2	-	k_2
Bus 3	k_2	k_2	k_2	k_3	k_3	k_2	k_2	k_2	k_2	k_2
Bus 5	-	-	-	-	-	k_2	-	-	-	-
Bus 6	-	-	-	-	-	-	k_2	-	k_2	-

The total planning cost is increased to $21.11M. This cost includes the installation cost of the IDC ($9.24M), the IDR ($2.53M), and the OC ($9.34M). Comparing with Case 1, it is shown that the installation cost of IDC and IDR were increased, whereas the OC is decreased. In addition, $322K was saved in total expansion and operation cost because of establishing data routes between the UGs. The LMPs were updated 3 times by the ISO in this case. The number of iterations for finding a feasible solution in the first, second, and third iterations of updating the LMPs are 3, 5, and 4 respectively. The total solution time is 8025 seconds.

TABLE VIII
EXPANSION OF DATA ROUTES IN CASE 2

Year	1	2	3	4	5	6	7	8	9	10
(UG_1, bus 3)	1	0	0	0	1	0	1	0	1	0
(UG_1, bus 6)	1	0	0	0	0	0	0	0	0	0
(UG_2, bus 2)	1	0	0	0	0	0	0	0	0	0
(UG_2, bus 3)	0	0	0	0	0	0	0	0	0	0
(UG_2, bus 5)	1	0	0	0	0	0	0	0	0	0
(UG_2, bus 6)	1	0	0	0	0	0	0	0	0	0
Year	11	12	13	14	15	16	17	18	19	20
(UG_1, bus 3)	0	1	0	0	0	0	0	0	1	0
(UG_2, bus 2)	0	0	0	0	0	0	0	1	0	1
(UG_2, bus 3)	0	0	0	0	1	0	0	0	0	0

3) *Case 3 – Deterministic solution with contingencies*

In this case, the contingencies because of failures in generation and transmission components were considered in the proposed framework. The forced outage rate (FOR) of transmission lines and generation units are 1% and 4%, respectively [49], [50].

TABLE IX
EXPANSION OF DATA CENTERS IN CASE 3

Year	1	2	3	4	5	6	7	8	9	10
Bus 1	k_1	k_1	-	-	-	-	-	-	-	-
Bus 3	k_1	k_1	-	-	-	-	-	-	-	-
Bus 5	k_3	k_2	k_2	k_2	k_2	k_2	k_2	k_2	k_2	k_2
Bus 6	k_3	k_1	-	-	-	-	-	-	-	-
Year	11	12	13	14	15	16	17	18	19	20
Bus 1	-	-	-	k_2	-	-	-	-	-	-
Bus 3	-	-	-	-	k_2	-	-	-	-	-
Bus 5	k_2	k_2	k_2	k_2	k_2	k_3	k_3	k_3	k_2	k_2
Bus 6	-	-	-	-	-	-	-	-	k_2	k_2

The results are presented in Tables IX and X. Comparing this case with Case 1, it is shown that the IDC modules were installed on buses 1, and 5 instead of buses 2, and 4. In year 1, line "2" and generator G3 are on outage in periods 3 and 7 respectively. Therefore, modules of type k_1, and k_3 were installed on buses 1 and 5 instead of bus 4 to ensure the electricity supply security for the IDC modules. As a result of failures in generator G2, and transmission line "1" in periods 2, and 11 in year 3, it is impossible to provide the required energy for the IDC modules located on bus 2. Therefore, compared to Case 1, IDC module of type k_2 was installed at bus 5 instead of bus 2. The total cost of planning is $20.81M; including the installation cost of the IDC ($9.19M), the IDR ($2.18M), and the OC ($9.44M). Comparing with Case 1, the total cost is increased by $590K and the OC of IDCs is increased by 5.82% because of outages in the electricity network. Ignoring the option of establishing data routes between UG_1 and UG_2 will increase the total cost to $20.93M, which shows a $120K increase in the total planning cost. The LMPs were updated 2 times by the ISO, and the number of iterations for finding a feasible solution in each iteration is one. The total solution time for this case is 5352 seconds.

The total number of variables in the master problem for deterministic solutions i.e. Case 1-3 is 7519 that includes 1440 integer variables, 800 binary variables, and 5279 continuous variables. The number of continuous variables in the electricity network security check sub-problem is 9601.

TABLE X
EXPANSION OF DATA ROUTES IN CASE 3

Year	1	2	3	4	5	6	7	8	9	10
(*UG*$_1$, bus 3)	0	1	0	0	0	0	0	0	0	0
(*UG*$_1$, bus 5)	1	0	0	0	0	1	0	0	0	0
(*UG*$_1$, bus 6)	1	0	0	0	0	0	0	0	0	0
(*UG*$_2$, bus 1)	1	0	0	0	0	0	0	0	0	0
(*UG*$_2$, bus 5)	1	0	0	0	0	0	0	0	0	1
Year	11	12	13	14	15	16	17	18	19	20
(*UG*$_1$, bus 5)	0	0	0	0	0	1	1	0	0	0
(*UG*$_2$, bus 5)	0	0	1	0	0	1	0	0	0	0
(*UG*$_1$, bus 6)	0	0	0	0	0	0	0	1	1	0

4) *Case4 – Stochastic solution*

In this case, the uncertainties in the demand, renewable generation, and availability of generation and transmission resources as well as the volatility in the rate of requests received by the UGs were considered. Using scenario reduction techniques, 13 scenarios with the probabilities shown in Table XI were considered. Tables XII and XIII show the outcomes of the expansion planning process.

In this case, 37 IDC modules are installed including; 12, 21, and 4 modules of type k_1, k_2, and k_3 respectively. The IDC modules are installed on all buses. The UGs are connected in years 1, and 16. The number of data routes installed between *UG*$_1$ and the IDC modules located on buses 1, 3, 4, and 6 is 2, 3, 3, and 1 respectively. Similarly, 2, 5, and 1 data routes are installed between *UG*$_2$ and IDC modules located at buses 2, 4, and 5 respectively.

TABLE XI
PROBABILITY OF SCENARIOS

Scenario	1	2	3	4	5	6	7
Probability (%)	88.8	0.2	0.2	2	2.2	2	0.2
Scenario	8	9	10	11	12	13	
Probability (%)	0.2	0.2	1.8	0.2	1.8	0.2	

TABLE XII
EXPANSION OF IDCS IN CASE 4

Year	1	2	3	4	5	6	7	8	9	10
Bus1	k_1	-	-	-	-	-	-	-	-	-
Bus2	k_3	k_1	k_1	-	k_2	k_2	-	-	-	-
Bus3	k_3	k_1	-	-	-	-	-	-	-	-
Bus4	k_1	k_2	k_2	k_2	-	-	k_3	k_2	k_2	k_2
Bus6	k_1	k_1	-	-	-	-	-	-	-	-
Year	11	12	13	14	15	16	17	18	19	20
Bus1	-	-	-	k_1	k_1	-	k_2	-	-	-
Bus3	-	-	-	-	-	-	-	-	k_2	k_2
Bus4	k_2	k_2	k_2	k_2	k_2	k_2	k_2	k_3	k_2	k_2
Bus5	-	-	-	-	-	k_2	k_1	-	-	-
Bus6	-	-	-	k_1	k_1	-	-	-	-	-

TABLE XIII
EXPANSION OF DATA ROUTES IN CASE 4

Year	1	2	3	4	5	6	7	8	9	10
(*UG*$_1$, bus 1)	1	0	0	0	0	0	0	0	0	0
(*UG*$_1$, bus 3)	1	0	0	0	0	0	0	0	0	0
(*UG*$_1$, bus 4)	0	0	1	0	0	0	0	0	0	1
(*UG*$_1$, bus 6)	1	0	0	0	0	0	0	0	0	0
(*UG*$_2$, bus 2)	1	0	0	0	1	0	0	0	0	0
(*UG*$_2$, bus 4)	1	1	0	0	0	0	1	0	0	0
Year	11	12	13	14	15	16	17	18	19	20
(*UG*$_1$, bus 1)	0	0	0	0	0	0	1	0	0	0
(*UG*$_1$, bus 3)	0	0	0	0	0	0	0	0	1	1
(*UG*$_1$, bus 4)	0	0	0	0	0	0	0	1	0	0
(*UG*$_2$, bus 4)	0	0	0	0	0	0	1	1	0	0
(*UG*$_2$, bus 5)	0	0	0	0	0	1	0	0	0	0

In years 1 and 2, *UG*$_1$ redirects part of the received requests to *UG*$_2$ to exploit the capacity of installed data routes between *UG*$_2$ and the IDC modules located on buses 2, and 4. In years 3-6, the IDC modules were installed on buses 2 and 4, where part of the requests of *UG*$_1$ is redirected to the *UG*$_2$. In year 16, the IDC modules were installed on buses 4 and 5 and another data route is established between the UGs to accommodate the increase in the rate of requests sent from *UG*$_1$ to *UG*$_2$.

The total cost of planning for this case is increased to $22.84M compared to Case 1. The installation cost of the IDC is $10.31M; the IDR is $3.15M and the expected OC is $9.38M. The total number of variables in the master problem for this case is 88159 that includes 18720 integer variables, 800 binary variables, and 68639 continuous variables. The number of continuous variables in the electricity network security check sub-problem is 124801. The LMPs are updated by the ISO in two iterations. In the first and second iterations, it takes 5 and 1 iterations to reach a feasible solution for the TOU respectively. The solution time is 8950 seconds.

C. *IEEE 118- bus system*

This case captures the IEEE 118-bus system with four UGs receiving the data requests from the end-users in the data network. In this case study, it is assumed that only one type of IDC module could be installed annually. A module in an IDC consists of 3500 servers (M=3500). Hence, the total power consumption of an IDC module considering full CPU utilization is 1.4MW. The installation cost of the IDC module with such demand is $2.8M [42]. The candidates for installing IDC modules are 23 buses in the electricity network. Each server in an IDC module will process 2 requests per second and the desired response time of the IDC modules is less than 300 msec. The annual growth rate of electrical demand is 3%. There are five wind generation units, each with the generation capacity of 150 MW. Here, the shape and scale parameters associated with Weibull distribution are set to 2.1 and 8.3, respectively. The rates of requests received by UGs in each period of the first year are shown in Table XIV. The expansion planning is performed for 20 years and each year consists of 4 equal periods each consists of 2190 hours.

TABLE XIV
RATES OF REQUESTS RECEIVED BY UGS (REQUEST PER SECOND)

Period	1	2	3	4
UG_1	6,954	14,476	20,840	24,630
UG_2	20,655	29,531	13,891	15,864
UG_3	7,518	15,428	20,459	25,767
UG_4	7,163	13,861	20,343	24,721

1) *Case 1- Deterministic solution without congestion*

In this case, 119 IDC modules were installed on buses 12, 17, 32, 37, 46, 49, 54, 56, 59, 62, 68, 69, 70, 80, 82, 86, 89, 91, 100 and 105. Moreover, 87 data routes were installed between UGs and IDCs, 3 data routes were installed between UG_1 and UG_2, 3 data routes were installed between UG_2 and UG_3, and 1 data route was installed between UG_1 and UG_4.

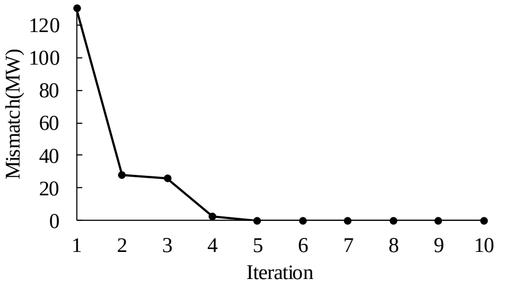

Fig.5. Mismatch in the electricity network security-check sub-problem at each iteration for the first iteration of updating LMP

The LMPs were updated 3 times by the ISO in this case. The number of iterations for finding a feasible solution in the first, second, and third iterations is 5, 3, and 4 respectively. Fig. 5 shows the number of interactions between the DCI and TOU to ensure the energy security for the installed IDC modules in first iteration of updating the LMPs. As shown in this figure, the mismatch in the electricity network security-check sub-problem reached zero after 5 iterations. This means that after 5 iterations, the decisions made by the DCI is feasible in the electricity network. The solution time for this case is 12558 seconds.

2) *Case2 – Deterministic solution with congestion*

In this case the capacity of the transmission lines 47, 48, 50-53, 62-64, 74-80, 82, 84-86, 104, 107, 158-160, 163,164 and 183 are reduced. In this case, 117 IDC modules were installed on buses 5, 17, 32, 37, 46, 49, 54, 56, 59, 62, 68, 69, 70, 80, 82, 86, 89, 91, 100 and 105. As a result of congestion, the number of modules installed on the buses is changed compared to Case 1. For example, the installed IDC modules on buses 37 and 56 are reduced from 16 and 15, to 4 and 8, respectively. As a result of congestion, the total cost is increased by $3.41M. The IDR and the installation cost of the IDC modules are increased by $6.52M and $570K respectively. The OC is decreased by $3.68M. The number of installed data routes between UG_1 and UG_2, UG_2 and UG_3, and UG_2 and UG_4 are 2, 2 and 2, respectively. The LMPs were updated 3 times by the ISO in this case. The number of iterations for finding a feasible solution in the first, second, and third iterations of updating the LMPs is 5, 2, and 3 respectively. The solution time for this case is 12407 seconds.

3) *Case3 – Deterministic solution with outages*

The FOR of transmission lines and generation units for this case is 1% and 4%, respectively. In this case, 117 IDC modules were installed at buses 12, 17, 23, 25, 32,37, 46, 49, 54, 56, 59, 62, 68, 69, 70, 80, 82, 86, 89, 100 and 105. The total cost is increased by $5.97M compared to Case 1. In this case, the OC, and IDR, were increased by 2.14%, and 15.23% respectively and the installation cost of the IDC was decreased by 1.1% compared to Case 1. In this case, 2, 3 and 3 data routes were installed between UG_1 and UG_2, UG_2 and UG_3 and UG_2 and UG_4, respectively. The LMPs were updated 3 times by the ISO in this case. The number of iterations for finding a feasible solution in the first, second, and third iteration of updating the LMPs is 5, 2, and 2 respectively. The solution time is 13455 seconds. The number of variables in the master problem of Cases 1-3 is 72931 that includes 9440 integer variables, 14480 binary variables, and 62043 continuous variables.

4) *Case4 – Stochastic solution*

In this case, using scenario reduction techniques, 13 scenarios with the probabilities shown in Table XV were considered. Here, 134 IDC modules were constructed on buses 5,12,17,23,25, 37, 46, 49, 54, 56, 59, 62, 68, 69, 70, 80, 82, 86, 89 and 100. The total cost is increased by $31.8M, compared to Case 1. The total number of data routes is 91 and the number of data routes installed between the UGs is 8. There are 3, 3 and 2 data routes installed between UG_1 and UG_2, UG_2 and UG_3, and UG_2 and UG_4, respectively. The outcomes of the expansion planning for all cases are summarized in Table XVI.

TABLE XV
PROBABILITY OF SCENARIOS

Scenario	1	2	3	4	5	6	7
Probability (%)	79.8	2.4	1.4	1.8	1.8	1.4	1.8
Scenario	8	9	10	11	12	13	
Probability (%)	1.8	1.6	1.8	1.4	1.4	1.6	

The LMPs were updated by the ISO in 2 iterations. The number of iterations for finding a feasible solution in the first, and second iteration of updating the LMPs is 5, and 2 respectively. The solution time for this case is 26307 seconds. The number of variables in the master problem is 767971 that includes 122720 integer variables, 14480 binary variables, and 630751 continuous variables.

TABLE XVI
PLANNING COST FOR ALL CASE 1-4

	Installation cost of IDC (M$)	IDR (M$)	OC (M$)	Total Cost (M$)
Case 1	135.84	27.44	153.72	317
Case 2	134.43	33.30	151.55	319.28
Case 3	134.34	31.62	157.01	322.97
Case 4	170.16	36.40	142.24	348.80

IV. CONCLUSION

In this paper, a coordinated expansion-planning framework for IDCs in electricity and data networks is presented. The proposed expansion planning formulation and solution methodology capture the uncertainties in the generation and transmission in the electricity network as well as the uncertainty of demand in electricity and data networks. Scenario based stochastic programming is used to solve the proposed problem and Benders decomposition is used to capture the interaction between the decision makers in the electricity network i.e. TOU, and the investor in the data network i.e. DCI. The objective is to minimize the installation and operation costs of IDCs and data routes in the electricity and data networks. The effect of congestion and unavailability of generation and transmission components in the electricity network on the expansion planning decisions in the data network was addressed in the case studies. It is shown that the interaction among the TOU, ISO and DCI improves the economics and energy supply security for the IDC modules. The congestion in the electricity network would change the expansion decisions in the data network because of the energy supply deficiency.

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