Centralized and Distributed Generated Power Systems - A Comparison Approach

Future Grid Initiative White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Centralized and Distributed Generated Power Systems - A Comparison Approach

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Executive Summary

The objective of the paper is to identify the strengths and weaknesses associated with Centralized Generation (CG) and Distributed Generation (DG) infrastructure for the future electric grid system. There are many reasons for considering the extent to which a planning and operation decision about CG and DG should be based. This will involve the development of indices for an economical scale study of DG relative to CG, and consider which is the most cost-effective to accommodate new markets. In order to assess the robustness of DG and CG under different load conditions, different indices for measuring the combination of CG/DG with respect to their capability and resilience to handling unforeseen events. This will involve development of new tools with stability measures and reliability as constraints.

Further, this paper evaluates the emission impact of the structure and its ability to diminish radiation, decrease emissions, and reduce environmental effects. This, again, will require new sustainability indices and predictive algorithm for proper measuring the trade-off between CG and DG.

Based on the analysis, and drawbacks and gaps in existing tools, new computational tools comprising decision support tools will be recommended as part of the research agenda to the development of co-optimization in a CG and DG based network for the future electric grid. With this attempt, this paper provides suggestions as to what extent the DG or CG will improve cost, sustainability, and resilience of the future grid.

Furthermore, suggested research activities to justify the most attractive combination of DG and CG are proposed. A research agenda, which includes development of advanced institutional reform, computational algorithms, and capacity building, is also proposed. These activities are presented in a time frame for implementation.

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1 Overview

The aim of this paper is to evaluate the relative benefits and weaknesses of centralized generation (CG) and distributed generation (DG) in the future electric grid infrastructure. The CG has been in dominant use in the legacy system, serving large consumptions of power but with a variety of problems including its cost, sustainability, and resiliency challenges in the long run. On the other hand, the DG is smaller in design and power generation, primarily designed for renewable energy resources (RER) such as wind and solar energy resources.

The paper is based on the analysis of using heuristic methods and engineering judgment to determine the extent to which the economies of scale of DG and CG are used to maximize the performance of the future grid. In addition, there is a discussion on what extent DG and CG can be co-optimized in the development of future grid.

Further, due to emission and variability issues and their impacts on the environment, indices for measuring sustainability are developed. These indices are proposed as the objectives to be satisfied in development of institutional arrangements for deployment of DG and/or CG or their combination to meet the challenges of developing the future electric grid.

Based on the analysis proposed, using advanced computational methods derived from decision support system and next grid optimization techniques that are capable of handling stochastic and dynamic systems, new grid infrastructure is proposed. The study also suggests activities that facilitate the national roadmap for developing the future flexible grid.

2 Proposed Objectives and Approach

Based on the objective of this paper, which is to identify the strengths and weaknesses associated with Centralized Generation (CG) and Distributed Generation (DG) infrastructure for the future electric grid systems, the criteria for these analyses will include the following questions:

1. To what extent are economies of scale still relevant for CG/DG?
2. Which is the most cost effective combination of DG and CG infrastructure?
3. To what extent does DG or CG improve system resilience to unforeseen events?
4. What is the most attractive combination of DG and CG infrastructures to maximize system resilience due to unforeseen events?
5. To what extent does DG or CG improve sustainability (i.e., decrease emissions and diminish other environmental impacts)?
6. What is the most attractive combination of DG and CG infrastructures to maximize system sustainability?

The following summarizes the approaches to the prior posed questions:

- In consideration of the economics of scale involved for the CG and DG system, a combination of both CG and DG would provide a more effective scale.
- Provided that consistent electricity and heat loads are available, proper DG penetration in CG could attain the lowest cost technology.

- Since the resilience of a power grid is dependent on power consumption, a DG system can be said to be of better resilience than a CG system.
- To eliminate emission, the mixture of DG and CG is pertinent to be implemented.

Sustainability could be achieved by elimination of emission. In addition, some components of DG, such as wind, solar, and biomass, make significant improvements to sustainability. During extreme events, the sustainability of the power grid is limited with DG. The role of CG, if elimination of emission is possible, is considerable. Therefore, a combination of the CG and DG is open for discussion.

Also, for the analysis to be incorporated in a decision support tool for determination of the optimal mix of DG and CG, the following tools are proposed [43, 44, and 45]:

1. Decision support tools - Analytic Hierarchy Process (AHP), game theory, and heuristic programming.
2. Optimization methods [43] based on goal programming with stochastic programming for decisions under uncertainty constraints, as well as dynamic stochastic programming.

Based on the proposed analysis and recommendations, the white paper will also provide a national roadmap as a guide towards identifying the right path forward in terms of which combination of DG and CG resources would make sense.

3 DG and CG Technology in the Future Electric Grid

3.1 DG Technology

DG is not a new concept. A number of utility consumers have been using DG for decades. Over the last 10 years, the DG market has been somewhat turbulent. In the late 1990s, new regulations/subsidies, such as net metering and renewable portfolio requirements, and the development of new DG technologies, have sparked broader interests in distributed generation. DG is power generation built near consumers. DG sources include small-scale, environmentally-friendly technologies (e.g., photovoltaic and wind) installed on and designed primarily to serve a single end user's site. But when reliability and power quality issues are critical, DG most often includes more traditional fossil fuel fired reciprocating engines or gas turbines.

The limited generation in the power sector has continually been exacerbated by load growth, power demand, limitations in the ability to site new transmission lines, limitations in the ability to construct large scale generation due to increased environmental regulation, and lack of technology development to meet the new requirements. Manpower is required to achieve the development of a sustainable, secured, and economically-viable society and infrastructure. The growth in developed and developing countries has created an energy divide in terms of wealth. The major disparities of energy consumption per capita are reflected in developing countries. The universal electrification challenge to meet the world's population growth in order to attain its current per capita electricity consumption will require massive increases in electricity generation capacities.

In some cases, properly planned and operated DG can provide consumers, as well as society, with a wide variety of benefits. These include economic savings because of government subsidies and improved environmental performance. Many utilities have installed DG on their systems and support federal funding of research to develop new technologies.

The interconnection of DG with the electric grid continues to pose genuine safety and reliability risks for the utility. DG could reduce the demand for traditional utility services. DG also poses an economic risk to incumbent utilities and their consumers unless appropriate rate structures or cost recovery mechanisms are put into place.

Though a small scale power plant, DG is environmentally friendly due to its "friendly" technologies. These "friendly" technologies include: photovoltaic's (PV), fuel cells, small wind turbines, or more conventional technologies such as: micro turbines and reciprocating engines that are fueled by renewable fuels, for instance, landfill gas. DG encompasses generation built near to a consumer's load despite size or energy source. The latter definition could include diesel-fired generators with significant emissions.

Other definitions of DG include some or all of the following:

- Any qualifying facilities under the Public Utility Regulatory Policies Act of 1978 (PURPA);
- Any generation interconnected with distribution facilities;
- Commercial emergency and standby diesel generators installed, (i.e., hospitals and hotels);
- Residential standby generators sold at hardware stores;
- Generators installed by utility at a substation for voltage support or other reliability purposes;
- Any on-site generation with less than "X" kW or MW of capacity. "X" ranges everywhere from 10 kW to 50 MW;
- Generation facilities located at or near a load center;
- Demand side management (DSM), energy efficiency, and other tools for reducing energy usage on the consumer's side of the meter. The alternative to this definition would be to abandon the term "distributed generation" completely and use instead "distributed resources" (DR) or "distributed energy resources (DER)".

3.2 CG Technology

Central Generation or CG is the electric power production by central station power plants that provide bulk power. Most of them use large fossil-fired gas or coal boilers, or nuclear boilers to produce steam that drives turbine generators. In some cases, large hydro is also used. These enormous plants require costly management of large infrastructures. CG plants are susceptible to unreliability and instability under unforeseeable events, and are often vulnerable to attacks. Their limitations, in terms of efficiency and environmental impact as well as stability to sustain them, have given rise to renewable energy resource options for researchers and policy-makers.

Both a centralized generated grid system and a distributed generated grid system have their merits and demerits. Thus, this white paper aims at enumerating both positive and negative aspects of the grids as well as addressing the challenges posed by the grids. This analysis helps to assess the best option that may enhance the reliability, resiliency and sustainability of the current grid architectures.

4 Criteria for CG/DG Comparison

The criteria for CG/DG comparisons presented will invole the economies of scale study of DG relative to CG, and consider the most cost-effective combination that can accommodate new markets. This is relative to CG, and considered the most cost-effective combination to accommodate new markets. Criteria for a CG/DG comparison include:

- Economies of scale: the advent of steam turbines made it possible to increase the size of the turbines while decreasing the marginal cost of electricity production.
- High energy efficiency: gains in efficiency were achieved through larger facilities that are capable of withstanding higher stem pressures and temperatures used in electricity generation.
- Innovation in electricity transmission: the use of alternate current as opposed to or direct current is permitted to transmit electricity over long distances without a significant loss or reduction.
- A search for reliability: so as to increase the reliability at the customer's end, large electricity production facilities were connected to the transmission networks.
- Environmental constraints: the use of transmission networks made it possible to relocate the generation facilities outside the city centers thus removing pollution due to exhaust from coal fire plants.

Other criteria for the comparision of CG/DG is to evaluate the resiliency of the combined infastructure, the impact on sustainability due to CG/DG or both as it relates to diminishing radiation, decreasing emissions, and reducing environmental effects.

The criteria for CG/DG comparisons presented throughout the white paper will involve the economies of scale as it pertains to DG. Another criterion for the CG/DG comparison is to evaluate the resiliency and sustainability of the combined infrastructure and determine the most effective combination of CG/DG aimed at meeting the needs of the future electric grid.

The sustainability impact of CG or DG or both CG/DG combined relates to diminishing radiation, decreasing emissions, and reducing environmental effects. This criterion is used to assess the optimal combination of CG/DG to meet demands under assortments of power and seasons of the environment.

Non-related impediments that may affect DG installation include: relatively small size, high cost (federal and local subsidy for renewable generation may not be sustained), internment power production, power quality issues, etc. Due to the benefits above and cost implications shown in Table 1, the comparative analysis for valuing DG and CG for meeting different load demands in the future grid is demonstrated.

The knowledge from an analysis on the criteria above helps to determine a sequence of activities for designing the future grid. It is an attempt to build a feasible future grid that will meet the growing demand of the population worldwide. Furthermore, the institutional arrangements, standard requirements, and capacity building are a part of the proposed road map which guides the nation's involvement in the new flexible grid.

With these criteria, the paper provides a national roadmap as a guide towards identifying the right path forward in terms of which combination of CG and DG resources would make sense.

Table 1: CG and DG Values and Recommendations

Value	**Distributed Generations**	**Centralized Generations**	**Recommendation for CG and DG options**
Continuous Power	Operated to allow a facility to generate some or all of its power on a relatively continuous basis. Important DG characteristics for continuous power include: ▪ High electric efficiency, ▪ Low emissions.	Though operated to provide continuous power, its characteristics results in: ▪ Low electric efficiency as a result of high losses at the transmission system ▪ High emissions	For continuous power production, more DG need to be penetration in CG based networks to reduce emissions and increase efficiency.
Premium Power	It provides electricity service at a higher level of reliability and power quality than typically available from the grid.	Provision of power at low reliability and power quality cannot be guaranteed due to inherent high power losses.	Providing premium power would also need DG penetration in the CG network leading to better reliability and low losses.
Cost	Low variable cost Low maintenance costs	High variable cost High maintenance cost	With respect to cost, DG based networks is preferable.
Peaking Power	Operated between 50-3000 hours per year to reduce overall electricity costs.	It is operated unintermittently at various peak powers.	Combined CG and DG.
Resiliency	More resilient since it serves low power demands continuously.	Less resilient but serves high power demands continuously.	Combined CG and DG.
Sustainability	Sources of power makes it more sustainable	Sources of power results in less sustainability	More of CG is preferable.

5 Technical and Economic Issues Facing Distributed and Centralized Generation

Generally some distributed generation systems are geographically distributed and can be located near to region of power consumers. This reduces transmission and distribution losses by robust terms based upon the very large numbers of individual generators and statistical robustness of such a collection compared [7] to centralized generation. This is a simple manufacturing technology when compared to CG. However, the RER still has limitations which include:

- The cost of electricity in some cases is higher than the ones form CG (i.e., “hidden costs”).
- In general, they cannot be dispatched except biomass.
- CG’s distributed nature may require restructuring of the electricity supply infrastructure.
- Evolution of the electricity networks will be found in future distribution networks where automatic network reconfiguration schemes aimed at facilitating high penetration of DG while reducing systems down time due to faults. This can be found in transmission and sub-transmission active networks with high voltages. In a situation where a distributed generation (DG) system is embedded in the system, there will still be a number of technical implications.
- Fault levels will increase when the DG is installed. This of course will economize the size of DG.
- In network security, the size will be limited seeing that a DG has to comply with set standards rather than to simply meeting supply security at the pre-reconnection point which will require more control options for better security though at higher budgeted cost.
- Voltage level of radial type system supply a number of distributed consumers with DG at different locations which will increase local voltage level and cost implications.
- Network stability issues under fault condition leads to system dynamics which may cause instability depending on the characteristics of the DG. If this occurs, appropriate control systems have to be included at a cost to overcome the instabilities.

Additional benefits of DG (not including RER) interconnection to the future grid include:

- Electric system reliability increases
- Supplies urgent power demands
- Peak power reduction
- Power quality improvements
- Infrastructure resilience improvement
- Land use effects reduction
- Vulnerability reduction.

The vast majority of electric power generated by DG as described in this paper is provided directly to consumers without being transmitted or distributed by means of the power grid. Such DGs supplying consumers’ power are termed “stand-alone”, while those that are connected to the power grids are referred to as “grid-connected”. This clearly shows that energy reliability could be enhanced with DG.

Even though DG has the enumerated benefits, a proper interconnection to the power grid is necessary to forestall undesirable consequences to local electric system operations. The usage of proper interconnection and control devices can be done to ensure a seamless transition when the DG is not operating.

In a Centralized Generated (CG) power system network, the transmission of power is carried over long distances from the centralized system before making the generated power available to consumers through distribution networks. At the generating end, power should be generated with different sources such as: hydropower, nuclear power, thermal power, and more. In regions where a Centralized Generated system is quite far from users, a need arises for such centralized systems to be decentralized. This act reduces transmission of power losses.

6 Economies of Scale of CG/DG

The widespread need for an increasing power demand has increased the need for better economies of scale [2]. Most power plants are built due to a number of economic, health and safety, logistic, environmental, geographical and geological factors. For example, coal power plants can be built far from cities to prevent their heavy air pollution from affecting the populace. These plants are often built near collieries to minimize the cost of transporting coal. Hydroelectric plants are usually limited to operating at sites with sufficient water flow. Power plants are often considered to be too far away for their waste heat to be used for heating buildings. Low pollution is an important advantage of the combined cycle plants that burn natural gas. The low pollution assists the plants in being used close to a city for district heating and cooling.

Another approach for promoting economies of scale is localized generation for Distributed Generation. The amount of energy lost in transmitting electricity is reduced because the electricity is generated near to where it is used, sometimes even in the same building. This also reduces the size and number of power lines that need be constructed. Typical distributed power sources in a Feed-in Tariff (FIT) scheme [6] have low maintenance, low pollution and high efficiencies, but because most FIT tariffs require use of intermittent renewable resources, reliability and power quality issues become important. In the past, Distributed Generation as described in this paper required dedicated operating engineers and large complex plants to reduce pollution. However, modern embedded systems can provide these traits with automated operation and renewable resources, such as sunlight, wind and geothermal. This reduces the size of power plants that can yield profit.

6.1 Economies of Scale in Power Demands

As power demands increase, the ability of the power grid to enhance power reliability becomes indispensable. To ensure power system resiliency, sustainability and reliability, the present grid has diversified the technologies of power production. This technology has necessitated the demand for growth in the number of Distributed Generators. The same could be said about the Centralized Generators. However, due to the higher installed capacity and the increased siting and permitting obstacles, CG becomes more expensive or impossible to increase the number of CG operating in a region of power demand. Hence, as power demands increase, it costs less installing a DG to meet the increased power compared to CG. Recall also that the transmission of power cost for CG makes it highly non-economical when there is a new power production facility to be installed. A non-intermittent DG, on the other hand, has no need for a transmission network, thereby eliminating losses in transmission. It then becomes apparent by installing new power capacity plants: a DG has better [2] economies of scale than a CG.

Estimating the worldwide share of distributed generation can lead to significant divergence in results. This is due to the differences in the definitions used. The differences can yield significant adjustments in the estimate of the total share of Distributed Generation. The inclusion or exclusion of large cogeneration facilities can significantly affect the results. For instance, the total share of Distributed Generation is 2.5% [8] in California if cogeneration capacities larger than 20MW are excluded. If included, the share goes up to 17% of the total net peak demand [8]. The bone of contention here is whether this large cogeneration capacity often connected to the transmission grid can be considered as Distributed Generation. The impact on the result is even more significant as the capacities of such facilities tend to be high. Two final impacts of DG incorporation into the grid are natural gas and emissions of CO_2, SO_2 and NO_2. The widespread penetration of DG shows that these emissions are reduced drastically for renewable energy resources when comparison is made with respect to coal.

Traditionally, generated power sources produced by non-utilities are mostly used in emergency situations and standby power systems. These Distributed Generators though have minimum impact with the utility's power. At present, the hardware to implement distributed generation interconnection to the grid has increased the utilization of DG output in meeting various energy needs, thereby offering nonutility-generated power sources, such as emergency and standby power systems.

7 Cost Implication for CG and DG

With the technologies involved for Centralized Generation and Distributed Generation, it becomes essential to compare the costs that could be incurred in a typical design layout of both CG and DG. Since DG will continue to be a potential source of viable energy that enhances uninterruptible power, expanding the role of DG in the power grid of the future could totally be based on whether the [1,6] costs of DG is lower than CG.

For capturing small niche markets of power demands, by producing power directly at the site of usage, power by Distributed Generations would be more valuable at or very near the retail price of generated electricity since it displaces utility-provided power. A small power generation project like DG is also less likely to have negative impacts on land uses. This goes a long way justify installing more DG than CGs.

Given the same region of power to be supplied, Table 2 depicts the cost involved in using either a Centralized Generation system or Distributed Generation system. Provided that consistent electricity and heat loads are available, DG is the lowest cost technology. By restricting the technologies available to the model, optimal system solutions using DG can be compared to an energy system using conventional *electricity-only* and *heat-only* technologies. Will DG provide economic savings for an entire system?

Table 2: CG and DG Cost Implication

Component Cost	Centralized Generation (CG)	Distributed Generation (DG)	
Cost of Capital	Lower Cost per unit	Higher cost per unit Saved cost of system design due to reduced capacity Saved cost of system design due to use of waste heat in cogeneration	This approach would lead to a reduced cost for the power grid system with the combined CG and DG.
Fixed Operation and Maintenance Cost	Higher	Lower	This approach would lead to a reduced cost for the power grid system with the combined CG and DG.
Variable Operation and Maintenance Cost	Lower	Higher	
Fuel	Same as DG	Same as CG	
Transmission	High voltage transmission is mandatory High losses and transmission failure	Only distribution required Reduced capital cost	This approach would lead to a reduced cost for the power grid system with the combined CG and DG.
Expense for Unserved Energy	High	Low	

8 Economic Pricing Benefits for CG and DG Systems

Another approach to determining the value of DG over CG is to determine the benefit [1] marginal price of DG over CG to the customer, and to the utility to determine the value of reliability. This is an area of research worth pursuing. This effort will also allow us to compute the outage cost to determine the value of DG to improve reliability of the network. Locational marginal pricing [1] that addresses the need for transmission congestion clearly defines that a need arises to limit power flows in a transmission system. This is essential so that resulting stability and voltage are kept within acceptable limits.

In a situation where an incremental load has a cost associated with it such that the bid price of the next unit in an economic order, then the lowest associated cost generator will not be sufficient to supply loads increment at some locations. Since a generator pays nodal prices and load pays the nodal prices, then the congestion charge is associated with difference between generator and load nodal prices. This price is rather low with a DG system compared to a CG system. Hence, a DG system supplying power in same region as a CG has a lower congestion charge implying that the DG network is prone to power system stability as against the CG system.

Centralized Generated (CG) systems have a high cost of installation and maintenance; however its usage is mainly from a central location. When compared to several installations and maintenance of a DG system, clearly a CG could be considered less expensive. For a region with a CG system and same region with DG, it is less expensive to supply power to users with the CG though losses in the CG architecture would be greater than DG system comprising up to about several dispersed generation evenly to meet the demands of power consumption.

In consideration of the economies of scale involved for the CG and DG system, the combination of both CG and DG would prove to attain a better scale. In regards to this, consideration should be given to densely populated regions. Either the CG system is installed closer to such a densely-populated region to minimize losses or a DG is installed at such location to minimize same effect. This combination therefore will further ensure less installed capacity for either a DG or a CG system, thereby optimizing the cost implication involved in their set up.

9 Resilience of CG and DG Systems

Resilience is the ability of a system to respond and recover from an event. In other words, it is the response of the system to recover from a catastrophic event such as a hurricane, or earthquake. The resilience prevalent in either a CG or DG system is the property associated with the system such that increased or decreased load demand is appropriately compensated with increased or decreased supplied power. Resilience required in a CG is therefore not the same as that necessary for a DG. This is because the load demand required for a CG is higher than a DG. In compensating this higher load demand for a CG, recall that that the installed capacity for the CG is greater than DG.

Today's energy availability to users is largely dependent on the resiliency of the power grid supplying the need of the consumers. The study of economics has proved that provision needs to be taken into consideration should power demand exceed power generated. In a particular region under consideration, required energy consumption increases with population. Therefore, a need arises to have a power grid expansion options during the installation of either a DG or CG systems.

We could argue that the unit commitment approach to power system planning and operation is the solution to this challenge. The unit commitment only takes into consideration the optimization of generated or supplied power to consumers. Both DG and CG systems could be optimized to meet the everyday need of power consumers. However, in the advent of a population increase, a need arises to increase the capacity of either the CG or DG commensurate with increased power consumption. Since CG is larger and covers more diverse types of loads, the diversity factor is an advantage for CG.

Given the fact that losses are prevalent in a CG system and the cost of installation is on the high side, a better option to cater to the need of ever increasing power demand would be the DG systems. A decentralized option for DG could very well be an option, but the expense involved in the setting up of a DG with nature re-plenishable renewable energy makes the CG more preferable. It should be noted that resiliency expands on vulnerability and may be viewed as the ability of a CG or DG system to return to its fail-safe state in the shortest time possible. To attain measure of resilience of CG or DG, a performance matrix is proposed, including reliability, stability and their contribution to resilience.

9.1 Measures of Resilience in CG/DG

Resilience metric is defined as:

$$R(x,u) = \int_t^n [\sum_{i=1}^{n} c_i f_i(x,u)]dt$$

This could be used as assessment of the resiliency [4] of DG or CG systems where $f_i(.)$ is the routine task, such as power supply and transmission transactions, and/or communication services, with weight coefficient c_i as an associated cost at a given time scale; x and u are the state and control variables, respectively.

DG is expected to be more resilient than CG; a higher metric of resiliency is understandable in a grid with CG and DG networks. Resiliency in DG systems is high due to better self-healing capability as compare to CG. Fault cases in CG have less severe impacts on the grid because they serve smaller regions that CG. In extreme cases of natural disasters such as hurricanes and tornadoes leading to faults on the grid, a CG-based network would likely be more affected with less effect on a DG network with planned islanding capabilities.

9.2 Enhancing the Reliability of Power Grid

As CG/DG systems continue to grow in size and capabilities, the current state of art in power system reliability is being pushed to its limit. While power engineers try as much as possible to ensure that there is constant power availability to users, considerations of some natural disasters such as earthquakes, hurricanes, tornadoes, and snow storms, continually mitigate the [5] availability of continued power being supplied to these consumers. The question to be addressed now is: will either CG/DG or both power grids architecture be best to improve the reliability of power consumption?

A Centralized Generated system has a central location of power being generated before the generated power is transmitted, distributed and made available to consumers. Clearly, power generated at the central station cannot be the same as the total sum of power supplied to consumers.

A Distributed Generated system on the other hand has its location closer to power users. The architecture there is not dependent on the transmission network. Hence, losses inherent in DG architecture are far less than the CG system.

In determining the reliability of a DG, indices are necessary to have accurate understanding of the extent of reliability.

9.3 Some Measures of Reliability

Some measures of reliability [8, 20] are defined as:

(1) Expected Unserved Energy (EUE): Measure of transmission system capability to continuously serve all loads at all delivery points while satisfying all planning criteria. It requires the following information for its computation:

1. Frequency of each contingency (outage/year)
2. Duration of each contingency (hour /outage)
3. Unserved MW load for each contingency

EUE = sum of all the probabilistic weighted unserved MW for each contingency.

Where:

$$EUE = \frac{\sum_{i=1}^{N}\sum_{y=1}^{Y}\sum_{d=1}^{D}\sum_{h=1}^{H} E_h}{N_h}$$

EUE = Expected Unserved Energy (MW-hours/hour)

N = the number of Monte Carlo simulations for the period, which is typically one year using hourly level of granularity

Y = number of years in the study

D = number of days in each year that are simulated

H = number of hours in each day that are simulated

E_h = the amount of unserved energy for this hour (in megawatt-hours)

N_h = the total number of hours simulated in the Monte Carlo study.

(1) **Loss of Load Probability (LOLP)** in units of percent, measures the probability that at least one shortfall event will occur over the time period being evaluated.

Where:

$$LOLP = \frac{\sum_{i=1}^{N} S_e}{N}$$

LOLP = Loss of Load Probability (%)

S_e = Simulation in which at least one significant event occurs.

N = the number of a Monte Carlo simulations for the period, which is typically one year.

Table 3: Recommendations of Factors Affecting Resiliency in Combined CG and DG

	Factors	**DG**	**CG**	**Recommendations**
1	Reliability	Low reliability but has power output limitation	High with more output power	Combined DG and CG with more DG in the grid
2	Stability	Better stability	Less severe impact	Combined DG and CG with more CG in the grid
3	Faults in the grid	Less severe impact	Severe impact	Combined DG and CG with more DG in the grid
4	Extreme unforeseen events	Reduced vulnerability	Vulnerable	Combined DG and CG with more DG in the grid

10 Sustainability in CG and DG Systems

Sustainability of a power system network [11] is the capacity of the power grid to withstand load requirements and meet the power consumer's need. Previous evaluations of CG and DG show that more installation capacity is required for a CG than a DG since the CG has more power demand on it than a DG. But considering the cost of installation and ease of resource availability, DG systems could very well serve as a better option to meeting the increasing needs of consumers. Sustainability means the capability of critical infrastructures to persist functions or services in a longer term.

The use of DG has gained significance attention in a liberalized electricity market. It is expected to make a particular contribution to climate protection. This section of the paper investigates the advantages and disadvantages of DG according to the overall concept of sustainable electric power development.

A sustainability metric could be defined as:

$$T\,(\mathrm{S_r}) = P\,(\mathrm{S_r})\,(f\,(\mathrm{S_r}))^{-1} = [\sum_{j\epsilon \mathrm{S_r}}^{n} P_j\,]\,[\sum_{j\epsilon \mathrm{S_r}}^{n} P_j \sum_{j\notin \mathrm{S_r}}^{n} \lambda_{jr}\,]^{-1}$$

This could be used to measure the level of sustainability of either a DG or CG networks where contingency j at certain load level is characterized with probability pj and transition rate λ_{jr} is from and to other system states j, r. There are several and important drivers that aim at mitigating fossil fuel dependency thereby substituting these fuels for more sustainable sources of energy.

10.1 Power Quality

In simple terms, power quality is the measure of voltage quality at the end user. If the voltage is proportionate with the generated voltage by a constant ratio, then the power quality is said to be better. However, if the end user's voltage fluctuates constantly while the generated voltage remains constant, the power quality for such a system is very poor and thus a need arises for the assessment of such power quality. Power quality in a power grid network needs proper assessment as reliability of the grid is also based on the level of power quality in the grid. Favorably, the DG networks supplies power consumers' electricity over a small region of operation. Such power qualities to be addressed include: voltage sag, voltage swells, switching surges and harmonics.

The inclusion of power quality study to assessing the role of DG and CG based on fundamental criteria (that include steady state voltage rise, voltage fluctuation, voltage dip, generator start-up and static voltage stability) could be embarked on as selection of best power grid topology that minimizes cost of incorporation of DG, CG or both systems.

Recall that CG networks are over long distances as compared to DG networks. It therefore follows that a CG network system is more prone to voltage fluctuations, voltage dip, and instability when compared to a DG system designed to support the voltage. This, however, does not limit power quality challenges to a CG system. DG networks are excellent power grid networks that can be used to address a grid power quality challenges by the incorporation of storage systems (e.g., flywheels and super-capacitors,) and equipment usable as a power conditioner. Enhancing power quality can take on several approaches.

DG Grounding Issue: A grid-connected DG, whether directly or through a transformer, should provide an effective ground to prevent unfaulted phases from over-voltage during a single-phase to ground fault. DG can reduce power losses and defer utility investment for network reinforcing; on the other hand, the DG interacts with the power quality (PQ) of the distribution network. DG can introduce several disturbances causing a reduction of PQ levels, such as:

- Transients due to large current changes during connection or disconnection of the generators
- Voltage fluctuations due to cyclic variations in the generator output powers
- Long-duration voltage variations due to generator active and reactive power variations
- Unbalances due to single-phase generators
- Increased level of harmonic output.

Table 4: Some Power Quality Indices [8, 11, 42]

Index	Definition	Main applications
Total harmonic distortion (THD)	$\left(\sqrt{\sum_{i=2}^{\infty} I_i}\right) / I_1$	General purpose; standards
IT product	$\sqrt{\sum_{i=1}^{\infty} w_i^2 I_i^2}$	Audio circuit interference; shunt capacitor stress
Crest factor	V_{peak} / V_{rms}	Dielectric stress
Unbalance factor	$\lvert V_- \rvert / \lvert V_+ \rvert$	Three phase circuit balance

10.2 Sustainability and Development through DG

Sustainable energy has two key components: renewable energy and energy efficiency. DG encompass any generation built near to a consumer's load regardless of size or energy source. These include diesel-fired generators with significant emissions and large cogeneration facilities capable of exporting tens of megawatts of electricity to the grid.

The energy system lies at the core of sustainability just as balanced energy supply and demand can assist increase resource efficiency; minimize unwanted wastes thereby reducing the adverse environmental impacts of energy production. Sustainability in a DG system would thereby aim at addressing the following:

- Energy consumption reduction
- Reduction of sources of energy waste
- Minimization of energy production pollution
- Minimization of life-cycle costs of renewable energy resources
- Sustainability in CG and DG Systems

The following four scenarios can be used as comparison basis for the sustainability requirements from co-optimizing CG and DG. These factors can be used as criteria in selecting the mixture of DG and CG integration for developing sustainable electric supply chain and include:

- Environmental protection: concerns climate change and conservation resources. How each of this will contribute to electric power system sustainability will be compared.
- Health and safety in environment: this is an aggregate comparison to be undertaken depending on the location and type of technology use for DG.
- Security of Supply: here we need to look at the medium to long term availability or the diversity of fuel options from producing the power; consideration of low cost of availability reduction nor loss of grid or plant and also adaptability of DG to different fuel and resources.
- Economic impact: leads to job creation increase in production of services, innovation, flexibility and increase knowledge.

Renewable energy resources usable for a DG system could have some element of pollution if consideration is not given to the location of the installed DG. For example, consider a DG using wind energy as a renewable energy located in downtown region. Clearly, noise pollution is inevitable in such region of DG installation. Therefore, alternative renewable energy supply should be taken into consideration in such cases like this. We could employ solar energy as an alternative option of renewable energy resources in a location that is downtown while simultaneously requiring energy storage capabilities when unfavorable weather conditions such as cloud cover causes an abrupt change in power output.

On a local basis there are opportunities for electric utilities to use DG to reduce peak loads, to provide ancillary services such as reactive power and voltage support, and to improve power quality with non-intermittent DG or DG/storage combinations. Using DG to meet these local system needs can add up to improvements in overall electric system sustainability. Table 5 below compares some factors in CG that could be used in assessing the sustainability issues with respect to DG systems.

Environmental Concerns: Pollution and climate change effects are major concerns when it comes to a preferred power production technology. The centralized generation systems and most DG are aptly dependent on all forms of input energy that include the fossil fuels, among others. The majority of fossil fuels serve as combustion processes input since the products include pollutants: aerosols, nitrogen oxides and sulphur oxides. These pollutants are by far the major contributors to global warming as a result of the greenhouse gas emissions. Recent EPA regulations may limit the use of fossil fueled DG unless costly pollution control systems are applied.

Table 5: Sustainability Factors in CG and DG

S/N	Factors	DG	CG	Recommendations
1	Emissions	Low for intermittent source., High for fossil fueled units but has power output limitation	High with more output power	Combined DG and CG with more DG in the grid
2	Power Quality	Lower for intermittent sources unless combined with storage. Higher reliability and quality for firm sources.	Potentially lower reliability of power and quality	Combined DG and CG with more CG in the grid
3	Quality of service	Potentially better quality of service if combined with storage or power conditioning	Less quality of service	Combined DG and CG with more DG in the grid

10.3 Concerns for Deployment of DG for Sustainability

DG imposes a widely recognized risk to public safety that must be and can easily be addressed in any interconnection requirements. On most distribution systems today, power flows only one way. Even most distribution systems with two-way flows are still fairly simple compared to the interconnected transmission system, and the distribution utility will generally know which way power is flowing. Thus, if a line goes down, the utility will know whether the line is energized and can respond safely. Consumer ownership and operation of generation can change that unless the proper standards and safeguards are applied. Consumer-owned generation could unexpectedly energize a line that the utility believes is cold if applied improperly, with the possibility of injuring a utility worker or a citizen, or starting a fire.

Other interconnection provisions may exist to ensure the DG is not adversely impacting the utility grid and is safely interconnected with the grid. Unfortunately, the cost of mitigating impacts and ensuring safety sometimes makes the installation of DG less cost effective. For example, some organizations oppose utility requirements for small residential generators to have utility-accessible, lockable, visible disconnect switches. Installation of such devices can add costs to the interconnection, but assures that the utility system can be operated safely. The absence of such a switch can impose an unnecessary and unreasonable risk to the life and health of utility employees engaged in system maintenance.

In addition, the operator (1) has to keep generation and demand exactly balanced at all times; (2) to provide adequate “voltage support” on the lines; (3) to keep sufficient distribution capacity on all lines to move the power being used; and (4) to build and maintain sufficient generation, transmission, and distribution capacity to respond to contingencies, including the failure of lines or generators or the sudden addition or loss of large loads.

Moreover, that control process is location sensitive. Where generation and voltage support have to be located depends on the location of load and the design of the distribution system. That means that load, generation, and distribution facilities all have to be planned together. It also means that the addition or removal of a large load or generation source can require the construction of new distribution facilities; the re-engineering of existing distribution facilities; and/or the re-dispatching of existing generation facilities. The problem is further complicated because no two systems have the same structure or geography. One rule for responding to changes in system architecture may not work for any two systems or even for any two changes on the same system.

Further, every connected load is affected by the system topology. If an industrial customer that generates its own power drops load without simultaneously dropping generation, it could create a surge that damages utility control equipment as well as any connected electronic equipment operating in the surrounding neighborhood. If the industrial customer instead loses its generator without simultaneously dropping load, it could create destructive voltage sag. Provisions to prevent these types of issues must be addressed before the DG can be interconnected to the utility grid.

New generation sources can also change the direction and volume of power flows on the system, possibly causing some wires to be underutilized while overloading others. Those changes may require the distribution utility to reinforce its system, build new lines, or install new control equipment, generally at the expense of the DG developer

New generation could also force the system operator to re-dispatch the rest of the generation on the system. That is, it could require the operator to ramp down lower cost base-load plants and run more expensive peaking plants in order to maintain system reliability.

Obviously, the potential for transmission system varies widely according to the type and size of the installed generator whether the generator is intended to be isolated or operated in parallel with the system, or whether the generator is intended either to meet only a fraction of the consumer's load or to export significant amounts of power.

Most of the reliability risks discussed here can be addressed with the proper protection and monitoring equipment on the utility grid and/or the customer sides of the meter. The complexity and cost of such equipment varies widely depending on the size, application, location, and technology of the DG facility, the voltage at which it connects, and the size and architecture of the system to which it connects.

At present, environmental policies and economic subsidies are probably the major driving force for the demand for distributed generation in Europe. Environmental regulations and renewable portfolio standards force players in the electricity market to look for cleaner energy- and cost-efficient solutions. Here, distributed generation can also play a role, as it allows optimizing the energy consumption of firms that have a large demand for both heat and electricity, for combined generation of heat and electricity

11 Standards and Controls

Analytic evaluation of the consequences of DG systems could lead to quite a number of complex sets of social consequences. Wind energy being harnessed for DG for instance has been reported to be of immense noise pollution to surrounding environs, most especially if it is situated in close proximity to consumers. Environmental consequences as a result of land use, and waste heat are also some consequences to the benefits in DG.

In addressing these side-effects of DG, the Institute of Electrical and Electronic Engineers (IEEE) in 1999 started devising a universal interconnection standard for distributed generation interconnected with distribution systems. This was necessitated given the perception that major barriers or challenges posed by DG was as a result of inconsistent interconnection requirements between the DG and a power system network. By the winter of 1999, IEEE formed a working group to create the standards for the interconnection DG [14] and termed it IEEE P1547. Its purpose is to set up a uniform standard for distributed generation of 10MVA or less. These standardized requirements established in 2003 as IEEE 1547 are relevant to the performance, operation, testing, safety, and maintenance of the interconnection. This important standard, along with the accompanying standards, guides and recommended practices in the IEEE 1547 series have served the DG interconnection process well to assure a consistent, safe and cost effective interconnection to the electric power grid.

DG Penetration and Integration and Application Researchers have proposed how to handle challenges including encouraging new standards for probabilistic and random load patterns. Such standards will reduce costs in interconnection and penalties imposed on embedded generation. Extensive use of power electronics and control devices will be needed to aid the integration of RER and facilitate interconnection. In addition extensive use of communication and signal processing tools will be needed for real time allocation work. These issues are being addressed in the current activities of the IEEE P1547.8 working group

The use of planned islanding strategy will favor RER installations since the power system network will increase reliability but will require several cost increase of controls. Dynamic loads schedule under RER will increase opportunity to balance loads by proper frequency regulations and hence leads to innovative work in local control for demand side management which has not been properly addressed in research. The design and application of planned islands, or micro grids is addressed in IEEE 1547.4.

Another technology solution to RER and DG deployment is the use of storage technologies such as batteries, super-caps, high speed flywheels and regenerative fuel cells to address the intermittency and reliability of these kinds of DG.

The idea of self-sufficient energy efficient homes (smart homes or the evolvement of a micro grid) is another evolution of the increased development of DG, smart grid and virtual power stations. This is a cluster of distributed generation installations which is collectively run by a central control entity. The purpose of this is to minimize the random and probabilistic nature of resources making up RER.

Properly planned and coordinated additions of distributed generation can allow a system to postpone expansion of distribution or central station generation plants, provide reliability benefits, and save consumers money. But those benefits can only be achieved when the newly installed generation is planned in coordination with the utility responsible for serving that territory. Because of the nature of the electric grid, the addition of generation to a system is neither simple, nor without cost and risks.

12 Roadmap: A National Research Agenda for Development of the Infrastructure for the Future Electric Grid

Distributed Generation can be depicted as an attractive energy resource in the near future or long-term when the energy supply and capacity challenges becomes even more critical. There are numerous benefits in the use of distributed generation. Some of such benefits reiterated include: increased power supply efficiency, reduced line losses, greenhouse gas emissions reduction, decreased distribution and transmission infrastructure spending. With all these benefits coupled with enhanced security, stability and flexibility of the distributed generation, it thus becomes vital to evaluate the roadmap for distributed generation.

To develop a framework for development of CG/DG, a national research agenda for the development of the Infrastructure for the Future Electric Grid will include:

- Determination of costs and tradeoffs between CG and DG with respect to control costs, life cycle analysis, protection and maintenance for determining economies of scale
- Development of resilience, and sustainability metrics into power systems planning and operation which will help to evaluate stability margin, demand response, reliability issues of the system under resilience
- Determination of value added CG and DG incentives in terms of performance of the future grid under uncertainty, taking into consideration renewable energy, storage, plug-in cars, ramping, price response, and demand management of the grid
- Develop a new research thrust in areas of cost benefit analysis
- Develop better and faster algorithms which include adaptive predictive modeling with the capability of handling grid resiliency and sustainability
- Development of new curriculum and education to provide human capacity training.

13 Research Topics to Aid National Roadmap Agenda

The following research topics are posed to address a national roadmap agenda in determining the most cost-effective, resilient, and sustainable combination of CG and DG:

- Impact studies and analysis, which include reliability, stability, and network congestion
- Mitigation of market power
- The economic incentives to owners of clean DG technologies and the reduced health risks to society
- Reduced security risk to the grid
- Voltage support for the electric grid
- Land use effects: The value of reducing "foot-print" or space needed by generation, transmission and distribution infrastructures.
- System losses
- Combined heat and power/efficiency improvement
- Consumer options for participation in demand response
- Ancillary services. The value of providing spinning reserve, regulation, or other ancillary services with respect to the cost-benefit analysis study.

Table 6: National Research Agenda for Development of the Infrastructure for the Future Electric Grid

Roadmap	Factors	Combined CG and DG	Suggested Period of Roadmap
Research Activities One:	Economies of Scale: • Measurement • Capital Cost • Service Cost • Maintenance Enhancement • Land Use Cost	• Combined CG and DG will determine costs and trades off between CG and DG with respect to control costs, life cycle analysis, and protection and maintenance. • Mixture of CG and DG will determine incentives for renewable energy, storage, plug-in cars, ramping, price response, and demand management in the grid • Better use of new tools like phasor measurements, time of day pricing, and other intelligent infrastructure for system support is attained with mixed CG and DG. • The economic incentives to owners of clean DG technologies combined with CG leads to reduced health risks to society.	Short Term

Table 6: National Research Agenda for Development of the Infrastructure for the Future Electric Grid (continued)

Research Activities Two:	Resilience Matrix: • Measurement • Reliability • Stability • Protection	• Appropriate resilient metric applied to the power systems planning and operation would help to evaluate stability margin, demand response, reliability issues of the system under resilience for a more robust CG and DG.	Short Term
Research Activities Three:	Sustainability of Matric: • Measurements • Quality of Service Emissions • Environmental Impact • Power Quality	• To eliminate emission, the mixture of DG and CG is pertinent to deployed • Land Use Effects- The value of reducing space needed by generation, transmission and distribution infrastructure is promoted leading to reduced security risk to the grid for the CG and DG	Short Term
Research Activities Four:		• DG can reduce power losses and defer utility investment for network enforcing better than CG; on the other hand, the DG interacts with the power quality (PQ) of the distribution network.	Long Term
Advanced Computational Tools:	Tools for Handling Uncertainties: • Variability issues • Co-Optimization of resources	• Develop better and faster algorithms which include decision support tools, adaptive predictive model and state estimation for better management and planning.	Short, Medium. And Long Term
Institutional Arrangement:	Standards: • Regulations • Land use	• Land use in CG and DG comprises the institutional arrangement. This is aiming at addressing economics of scale, cost resiliency and sustainability benefits in combined CG and DG would better lead to institutional arrangement.	Short, Medium. And Long Term
Human Capacity Building:	• Educational and Training	• This work is aimed at developing new curriculum and education to provide human capacity training.	Short, Medium. And Long Term

14 Conclusion

This paper compared the merits and costs of co-optimizing DG and CG in a future electric grid. The various assessments of technology, cost, and maintenance have been identified to determine the extent to which DG or CG should be used to meet different uncertainties in demand growth. To provide answers to the posed objectives of this paper, it becomes important to evaluate the economies of scale for DG and CG technology. The factors (such as cost of maintenance, economies of scale, resiliency, sustainability, and ability to withstand growing demand) are discussed in this white paper. Therefore, a need arises for a decision support solver and optimization algorithm as suggested.

Furthermore, in the paper, we have evaluated the response of DG and CG to different catastrophic or extreme events which lead to system vulnerability and instability. A matrix of performance is proposed to include resiliency, stability, and reliability are defined to measure the grid-connected solely as CG or DG or in combination. The optimization scheme that includes power game and analytic hierarchy process (AHP) determine to what extent or mixture of CG and DG to be used in the face unforeseen attacks were discussed. This again has led to an evaluation of power quality and sustainability indices which help to determine the minimum combination which may pose health hazards.

The combined CG and DG network in terms of sustainability, resiliency, economics of scale, and cost are proposed to be used in determining the optimal combination of DG and CG in the future grid. To this end, following our analysis in the paper, we propose a national roadmap to promote research and open forum discussion in addressing strategic activity in achieving a future development of co-optimization of CG/DG that leads to a future grid. The issue of regulation, standards, and human capacity building are part of the outstanding issues in order to promote the development of this future grid.

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