Quantification of the Benefits of the *UIUC* Campus Utility System Operations as a Microgrid

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***Abstract*—The *US* grid's weak ability to withstand severe weather incidents, particularly the growing number of events due to climate change coupled with the slow pace of expansion of transmission grids and the increased push to integrate deeper penetrations of renewable resources have raised many questions on the reliability and resilience of electricity supply system. The increased implementation of microgrids (μgs) in distribution networks (*DN*s) indicates the realization that μgs provide promising alternative approaches to address these concerns. In light of μg benefits, the growing interest in μg implementation provides evidence that such benefits are actually being realized. In this paper, we report the application of a general, comprehensive simulation methodology, that explicitly represents various sources of uncertainty, to quantify the benefits of the *University of Illinois at Champaign–Urbana* (*UIUC*) campus utility system (*CUS*) operations under a μg paradigm relative to those under the current distribution–grid connected operational paradigm. The *UIUC CUS* consists of the electricity generation and distribution network and the steam supply system to meet the campus electric and cooling/heat loads. We conduct the *side–by–side* comparative assessment of the quantified operational performance of the *UIUC CUS* operations under the two operational paradigms so as to understand the extent to which the benefits of the μg concept application actually accrue for this specific system. The year–long comparison study provides insights into the improvements in the *CUS* average daily energy production costs, loss of load probability *LOLP* and expected CO_2 emissions under the μg concept application. Our quantification approach is capable to analyze and understand the impacts on the *UIUC CUS* operational performance by answering various "*what if*" questions including what if there is a change in the resource mix, maintenance schedules in the operation of the *CUS*, change in the policies in effect and many other issues. The simulation–based approach is an important new addition to the μg literature and the case study provides a good example of the limits of the μg application benefits.**

Index Terms*—quantification of μg benefits, simulation methodology, operational performance, side–by–side comparative assessment, performance metrics, combined steam and electricity systems, explicit representation of uncertainty impacts

I. Introduction

The *US* grid is increasingly subject to extreme weather incidents, such as, the *Superstorm Sandy* in 2012, causing serious damages with major social and financial impacts. From 2003 to 2012, about 679 power outages occurred due to weather events, with each affecting 50,000 or more consumers. These outages have estimated annual average costs of *\$* 18 – 33 billion in 2014 *\$* [1]. Furthermore, the deepening penetrations of integrated renewable resources into the grid increase the need for its expansion and also for effective grid operations so as to manage the variability and intermittency in the renewable energy outputs [2]. The d eployment of μgs in the *DN*s is a promising approach to address certain issues in the electricity system [3], [4]. A μg is a network of interconnected loads and distributed energy resources (*DER*s), within clearly defined geographic boundaries, with the properties that it is a single controllable entity with respect to the grid and that it operates either connected to (parallel mode) or disconnected from (islanded mode) the grid [5], [6]. The potential benefits in various μg projects gave rise to considerable interest in μgs everywhere. The rapid pace of μg development has resulted in a broad range of projects that vary in size from a few *kW* to several *MW*, depending on the specific application and the desired benefits. The effective exploitation of μg salient characteristics results in a wide range of benefits from grid reliability improvement to electricity supply cost reduction, and from facilitation of renewable energy resource integration to reduction in emissions [7], [8]. To bring about large-scale deployment of μgs in order to effectively harness potential benefits, a major challenge is to identify appropriate incentives for the construction of μgs in the grid. There is need for a proper assessment of μg benefits that may allow the formulation of the appropriate incentives directly aligned with the benefits. As such, the assessment of the μg benefits on an analytical level is well addressed in the current literature [9], [10]. But such an analytical assessment by itself cannot justify future investments in μgs.

There are few papers in the current literature that provide a study on the systematic quantification of μg benefits. We provide a brief review of some of the relevant work. References [11] – [13] assess and quantify the improvements in the reliability of electricity supply of the μg.. Reference [14] provides interesting insights into μg resource scheduling strategies for μg operations such as operating the μg to minimize costs of operation or minimize emissions production. In [14], the authors report on their deterministic analysis over a short period of time to illustrate the developed strategies. References [15] & [16] provide a quantification of the economics and emissions metrics of a power system operations with and without the μg concept application but without keeping the resource mix unchanged. As such, the benefits are viewed to be due to the resource mix changes rather than the μg paradigm operations. More specifically, in these two papers the metrics for emissions and economics are evaluated and compared for varying level of *DG* capacity in the resource mix of the μg. In [17], the authors make use of three cases for computation of reliability, economic and emission metrics: first where a feeder in a *DN* has no *DG*s, second with *DG*s and third when the feeder with *DG*s is operated as a μg. The authors compare the case 1 results with case 2 and case 3 together and the results for case 2 and case 3 are not provided individually. As such, the authors show the improvements in emissions, economics and reliability due to the deployment of *DG*s in *DN* but not due to the μg concept application.

In this paper, we aim to go deeper than the existing literature on the quantification of μg benefits by deploying a much comprehensive quantification methodology that may be used to reproduce with good fidelity the expected variable effects in terms of economics, reliability and emissions of the *UIUC CUS* when operated under current and the μg operational paradigm. A comparison of the metrics of interest obtained for the *UIUC CUS* operational performance under the current and the μg paradigm allows us to understand the extent to which the benefits of the μg concept application can be realized to the *UIUC CUS*. The quantification methodology used in the comparative assessment is comprehensive in a sense that it takes into account the uncertainty and time–varying phenomena in the *UIUC CUS* operations and is applicable over any specified period of time to capture the impacts of seasonal variations and maintenance schedules. Our quantification approach used in a comparative assessment framework ensures that the resource mix is kept unchanged[1] to make comparison meaningful. Our approach allows us to understand the impacts on the *UIUC CUS* operational performance by answering various "*what if*" questions including what if there is a change in the resource mix, maintenance schedules in the operation of the *CUS*, change in the policy and any other modifications of interest. The quantification approach is applicable to represent various sources of uncertainty in loads and resources, including the uncertain, time–varying and intermittent renewable resource outputs as well as conventional generator available capacities. The approach, while relatively straightforward to implement, can handle any type of renewable output probability distribution in addition to analytic distributions as our methodology does not require any assumptions on the shape of the distributions. The methodology is applicable to the quantification of the operational performance of any topological structure and resource mix composition of the μg. For the *UIUC CUS*, our quantification methodology is able to capture the inter–dependencies between steam and electricity system. The quantification methodology also captures the various sources of uncertainty in the *CUS* including the campus electricity and steam load, availability of generation resources along with their maintenance schedules, availability of the network *etc.* The year long simulation of the *UIUC CUS* under the current and the μg paradigm describes the relative improvements obtained if any on the economics, reliability and emissions metrics due to the the μg concept application to the *UIUC CUS*.

The paper contains four additional sections. In the second section, we describe the *UIUC CUS* and its current operations in detail. We explain the reasons which motivate the choice of *UIUC CUS* to be viewed as a μg that in turn allows us to use it for comparative assessment. We explain the simple steps required to operate the *UIUC CUS* under the μg framework which allows us to carry out a comparative assessment of the *CUS* operational performance under the current and the μg paradigms in terms of the relevant metrics. In the third section we provide an overview of our quantification approach in a *side–by–side* comparative assessment framework. In section four, we provide the details about the system schematic, data used in the simulation and the results obtained from the comparative assessment case study. In the last section, we provide concluding remarks with some additional insights gained from the *side–by–side* comparative assessment.

II. *UIUC CUS* Description And Operations

Since its founding in 1867, the University of Illinois' Urbana-Champaign campus has become one of the largest research institutions in the *US* with over 44,800 students and 10,000 faculty and staff. The campus has over 320 buildings on nearly three *square miles*. With the south farms included, the campus' 660 buildings cover over 7 *square miles*. The *UIUC* campus is a microcosm of a city with diverse facilities including the academic buildings and laboratories, student housing facilities, theaters, health center, sports stadiums, libraries and an airport. Some of these facilities, such as the health center and laboratories, are operational throughout the day. The *UIUC* campus is critically dependent on the *CUS* for the effective operation of this microcosm. We view the utility services provided on campus as an integrated utility system. The *CUS* serves the campus demands for the steam and electricity year round.

The *CUS* serves the electricity and the steam demand of the campus around the clock. The hourly electricity load varies in the [25,80] *MW* range during the year. The daily electricity load shapes for a week in March 2015, and one in September 2015, are shown in Figure 1. A salient characteristic of the loads observable from Figure 1 is the similarity of the daily electricity load shapes on each weekday and weekend day. Such a similarity stems from the fact that, when students are on campus, the electricity consumption remains independent of the day of the week.

The hourly steam requirement varies in the [80,500] *klb* range during the year. We provide illustrative examples in Figure 2 of the daily steam load curves for the 2nd week in January 2015 and the 3rd week in September 2015. We observe that the campus steam loads during a winter month

[1]A major point to understand with regards to μgs is that they only bring a change in the way a power system is operated. Therefore, the comparison of benefits of operating a power system as a μg with that when the power system is operated as is must be done with the resource mix kept unchanged under all operational paradigm to allow a meaningful comparison.

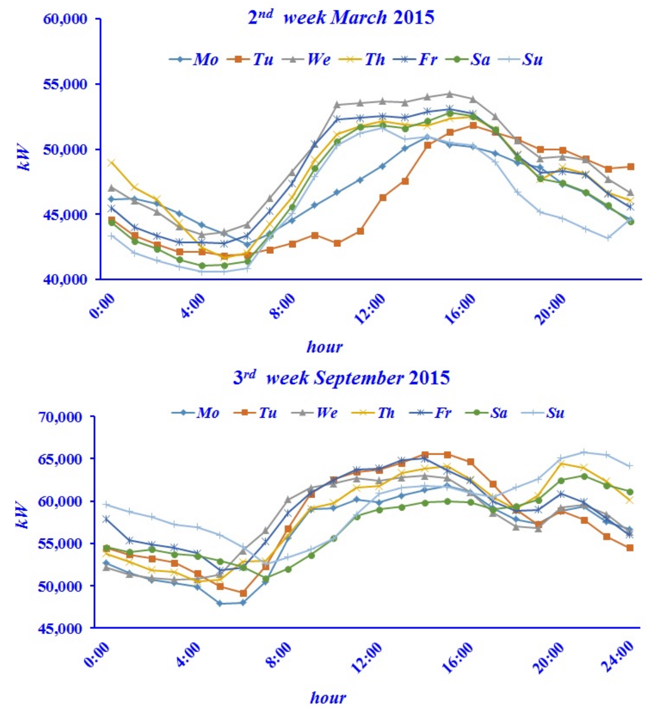

Fig. 1. *The campus electricity daily load shapes for a representative week in March* 2015 *and September* 2015

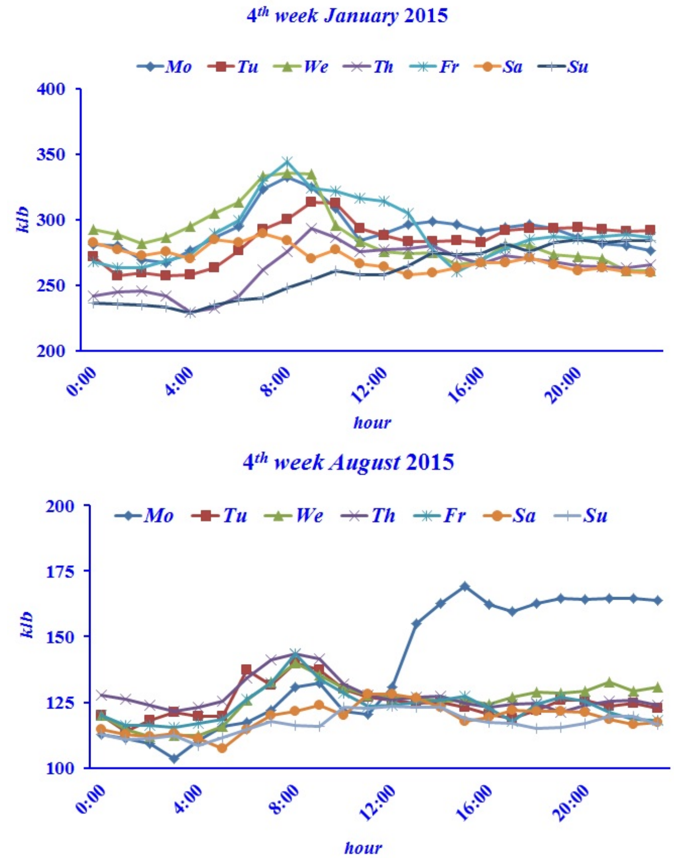

Fig. 2. *The campus steam daily load shapes for a representative week in January* 2015 *and August* 2015

such as February are much higher than those during a summer month, such as August.

To meet the campus electricity load, the *CUS* generates its own electricity at the *Abbott* Power Plant (*APP*) and the recently installed *UIUC* solar farm. The campus can also buy electricity in the Midcontinent Independent System Operator (*MISO*) wholesale electricity markets when the *APP* and the solar outputs are inadequate. *APP* is a combined heat and power (*CHP*) plant. The entire campus steam load is met by the steam produced at the *APP*. Currently, the *APP* has 9 steam turbine generators, four of which are the low–pressure steam units and the other five are the high–pressure steam units. The steam is produced by the five boilers in the *APP*. A single boiler produces low–pressure steam and the other four boilers produce high–pressure steam. Two boilers use natural gas, whereas the other three burn coal.[1] *APP* has two gas turbine generators which produce electricity. *APP* uses the heat recovery steam generation (*HRSG*) mechanism of the gas turbine generators to capture the heat that remains in the air–gas mixture used in the gas turbine generators. A duck burner (*DB*) is used to further heat the air–gas mixture after it passes through the gas turbines and the *HRSG* mechanism captures the heat, which is then applied to more water to produce additional steam. The steam generated from the operation of the *DB* and the *HRSG* mechanism is high–pressure steam. This high–pressure steam and the steam that passes through the high–pressure steam turbine generators is expanded to become low–pressure steam. This low–pressure steam and the steam that passes through the steam turbines of the low–pressure steam turbine generators is then distributed to the campus to meet the campus steam load. We display a schematic of the *APP* configuration in Figure 3. At present, the *APP* generates approximately 275,000 *MWh* annually, roughly 50% of the total campus annual electricity consumption.

In the 2015 *Illinois Climate Action Plan* (*iCAP*), *UIUC* set a goal that, by 2020, 12.5 *GWh* of electricity will be produced by solar installations on campus property. To meet this goal, *UIUC* signed a 10-*year* Power Purchase Agreement (*PPA*) with the developer *Phoenix Solar Inc.* to design, build, operate and maintain the solar farm called the *Phoenix Solar South Farm* (*PSSF*). The annual energy production from the solar farm is estimated to be 7.86 *GWh*. To supplement the outputs of the *APP* and *PSSF*, *CUS* buys electricity on the *MISO* market. The purchased electricity is transmitted from the injection node to a transmission node from which the delivery is made to the campus at the Main Substation (*MSS*) via the *Ameren DN*. At present, the import capacity from the *Ameren DN* is limited to 60 *MW*.

The existing *CUS* electricity distribution grid includes approximately 300 *miles* of electrical cable. In Figure 4, we show

[1]The boilers also have the capability to work on oil under emergency conditions.

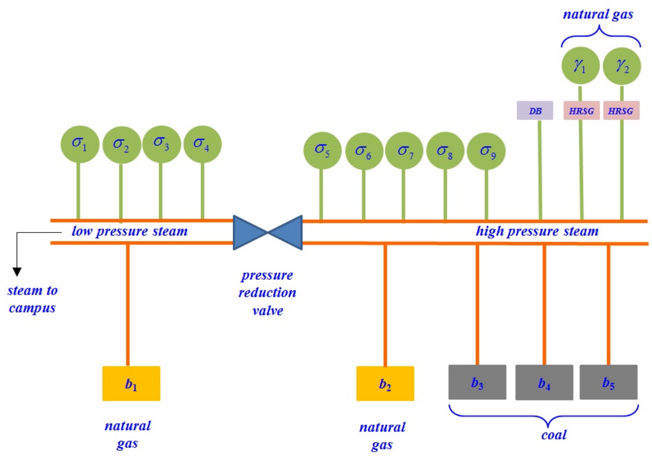

Fig. 3. *The schematic of the Abbott power plant layout*

the single line diagram of the *CUS* electricity distribution grid. This distribution grid is a 3–*phase*, medium voltage electricity network connected to the *Ameren DN* at a single point of interconnection – the *MSS*. The *MSS* is a 69–*kV* substation which is directly connected to the South–East Substation (*SES*) by s 69–*kV* distribution line of the campus distribution grid. The *APP* is connected to the *MSS*. There are 11 load centers (*LC*s) connected to the two campus substations and the *LC*s aggregate all the loads on campus. The *UIUC* solar farm is connected to the bus that serves *LC* 10.

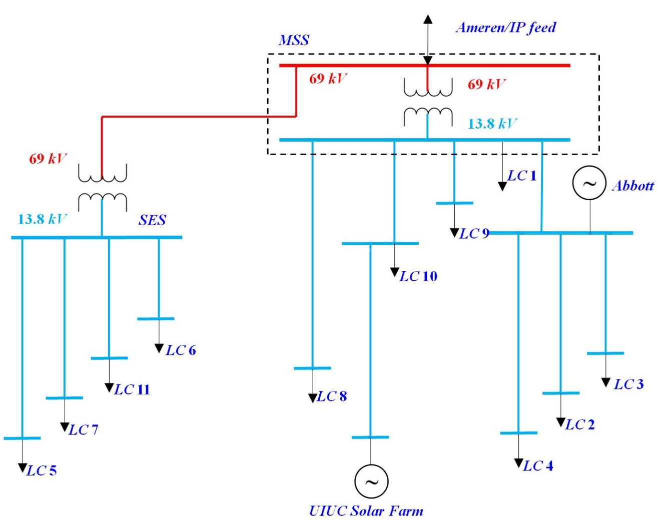

Fig. 4. *Simple single line diagram of the campus electricity grid*

The *CUS* objectives are to provide the steam and electricity services at all times in a reliable and an economic manner under the current paradigm. *CUS* is an integrated utility system with the two services – steam and electricity – that are strongly inter–dependent. The steam demand on campus determines the *APP* schedules and the electricity generated is thus a by–product of the *APP* steam production. The *APP* schedules, in turn, govern the purchase decisions on the amounts of electricity bought in the *MISO* markets to meet the campus electricity loads. These structural inter–dependencies among the two *CUS* utilities are so extensive that even if all the electricity consumption were supplied by renewable resources, the *CUS* still needs a certain amount of cogeneration to meet the campus steam demand. For the same reason, the *CUS* cannot buy all its electricity on the *MISO* markets even if the electricity is cheaper than *APP* electricity as *APP* still must cogenerate steam and electricity to meet the *CUS* steam demands. A division in the university called *UIUC* Facilities and Services (*F&S*) is responsible for the operation and maintenance of the *CUS*. The engineering outfit *Fellon–McCord* provides support for the *F&S* staff in terms of energy market and price information. This information, together with the daily electricity and steam load forecasts, is essential to determine the schedules and dispatch levels of the *APP* units. At present, the lack of appropriate data, forecasting information and tools analytically limits the efficiency of the *CUS* resource schedules. As such, under the current paradigm, opportunities for improvements in economics of operations may exist under different *CUS* operational paradigms.

Under the current paradigm, a key characteristic is that the *CUS* electricity distribution grid is connected to the *Ameren DN* at a single point of interconnection at all times. For the electric system in the *CUS*, if the *APP* units fail then, at present the *CUS* depends on the *MISO* wholesale electricity market and the *Ameren DN* to supply electricity to meet the campus electricity load. If the tie line connecting the *CUS* and the *Ameren DN* fails, even if the *APP* available generation capacity is more than the load, the *CUS* does not have the capability to run disconnected from the *Ameren DN* due to constraints from a protection as well as control standpoint. As such, the single point of interconnection of the *Ameren DN* and the *CUS* at *MSS* does not provide the flexibility to disconnect from the *Ameren DN* and operate the *CUS* as a single islanded system. Unlike electricity provision, if the *CUS* loses the *APP* units then *CUS* also loses the ability to provide steam for campus heating purposes as *CUS* cannot buy the steam on any wholesale market and most facilities on campus do not have the capability to produce and provide the heat locally at the facility itself. Similar to the discussion on economics of operations, opportunities for improvements in reliability of electricity supply to campus loads may also exist under different *CUS* operational paradigms.

We now explain as to how we can view the *UIUC CUS* via μg optics. With respect to the distribution grid size, a μg is a small power system containing a cluster of interconnected *DER*s and loads. Since a μg is a power system, all the attributes and functions of a large system, such as the bulk power system, hold. A μg differs from the conventional power system in terms of the coordinated control that the μg exercises on both the supply–side resources and the demand–side resources. A μg is a power system that operates in either of its two distinct modes: parallel, also known as grid–tied mode, or islanded, sometimes called the isolated mode. Due to the coordinated control over the μg generation as well as load resources, a μg may be viewed as a time–varying resource embedded in the *DN* with the ability to either generate or consume electricity or remain idle with 0 injection / withdrawal in the isolated mode operations. Under the coordinated control, a μg may exploit the opportunities to inject electricity into and provide *ancillary services* (*AS*) to the *DN* and earn revenues. μg loads may be classified as either critical loads or non–critical loads. The classification is essential for supply–demand balance under the islanded mode of operation. Such features provide added degrees of freedom in the operation of the grid with the integrated μg. In effect, the μg brings a new paradigm in the operation of the power systems. A μg not only ensures the reliability of the electricity supply to its critical loads but also takes full advantage of the *DN* when needed or opportune. In addition to the services taken from the grid, a μg is able to provide new operational degrees of freedom to the grid.

The *UIUC* energy resources – the *APP* and the *PSSF* – may be viewed as the *DER*s of the *CUS*. Based on extensive discussions with *UIUC F&S* staff, the classification of the campus electricity load into critical and non–critical loads is easily established. The campus grid forms an interconnected network of *DER*s and loads. As a *MISO* wholesale electricity market participant, *UIUC CUS* has the option to earn revenues for the sale of electricity and also has the option to exploit the opportunities for *AS* provision to the bulk grid in the *MISO AS* market. With the way *UIUC CUS* is connected to the *Ameren DN*, it has a defined geographical boundary in the *Ameren DN* footprint. Except for a few structural features, the *UIUC CUS* has all the required characteristics of a μg and fits the definition of a μg as it has the *DER*s in the form of the *APP* and the *PSSF*, critical and non–critical loads and a defined electrical grid boundary. Thus, we may view the *CUS* as a μg along with associated or required structural changes.[2] In Figure 5, we show a transformation of the *UIUC CUS* in a μg setting. Such a conceptual transformation allows the comparative quantification of the performance of the *UIUC CUS* as a μg to that under the current operational paradigm.

III. *UIUC CUS* OPERATIONAL PERFORMANCE QUANTIFICATION APPROACH

We make use of the conceptual transformation of the *UIUC CUS* as a μg in our simulation approach. For the quantification methodology, we use a stochastic simulation approach that provides the capability to quantify the impacts of *CUS* operations in terms of economic, reliability and emissions metrics of the *CUS* operations under a specified operational paradigm. The approach is based on the explicit representation

[2]Some of the key structural changes include the requirement of a flexible and a controllable interface between the campus electricity network and the *Ameren DN*, upgrades in the protection of equipment in the *CUS* for safe and effective operations of the campus μg in both grid–connected as well as islanded mode, continuous monitoring of measurements and the timely dissemination of the information among the players involved in the grid operations on a periodic basis and financial agreements among the players involved for the appropriate remuneration of the services used by the μg and provided to the bulk grid.

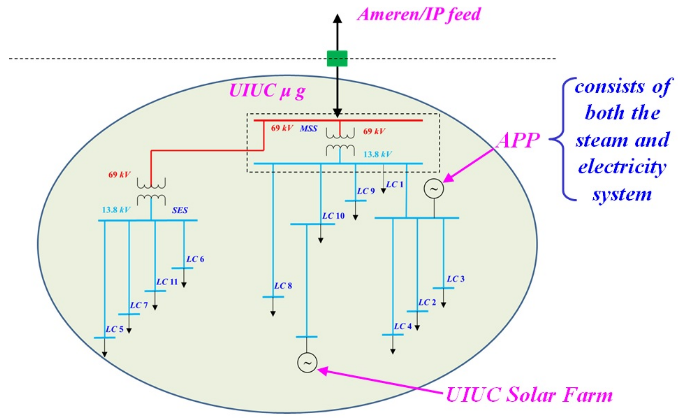

Fig. 5. *UIUC campus as a* μg

of the various sources of uncertainty together with the time-varying nature in the demand–side and supply–side resources in the *CUS*. The simulation approach models the uncertainty in the demands, available capacity of conventional generation resources and the time–varying, intermittent renewable resources in terms of discrete–time random processes (*r.p.s*). The modelling and sampling of the various sources of uncertainty (*s.o.u*) is well explained in [18], [19]. Such a representation explicitly takes into account the time correlations in each input variable. A key exponent of the simulation approach is the formulation of the so–called *energy scheduling optimization problem* (*ESOP*). The *ESOP* solution is an essential building block in our approach and is used to determine the *CUS* resource scheduling decisions with the explicit consideration of the uncertainty effects. Under the *current operational paradigm*, the schedule of the energy resources is based on heuristic techniques and does not involve the deployment of formal optimization techniques. The *ESOP* solution replaces the current heuristics–based approach to determine the optimal schedule and loading levels of the *CUS* energy resources so as to minimize the *CUS* operational costs. We use this optimal scheduling as a proxy for the current operational paradigm. In this way we can carry out on a meaningful basis a comparative analysis of the *UIUC CUS* operational performance as a μg – the so–called μg *operational paradigm* – and those under the optimal operations of the current paradigm. A modified *ESOP* and its solution is also adopted in the simulation methodology for the quantification of the *CUS* operational performance under the μg *operational paradigm*. The modified *ESOP* takes into account the added degrees of freedom due to the μg concept application. We explain the mathematical formulation of the *ESOP* and its modified version for the current optimal and μg operational paradigm in detail in [20]. A salient feature of the *ESOP* mathematical formulation is its ability to capture the inter–dependencies in the electricity and steam services that the *UIUC CUS* provides under each operational paradigm. The simulation approach makes use of the Monte Carlo simulation (*MCS*) techniques to represent the impacts of sources of uncertainty on the *CUS* operations under each operational paradigm and for the efficient sampling of the input *r.p.s* [18]. As such, we systematically sample the *r.p.*s to generate the realizations, or sample paths, that we use to emulate the scheduling of the *CUS* for a given operational paradigm via the *ESOP*. The *ESOP* solution maps the sample paths of the loads and supply resources into the sample paths of the *r.p.*s we use to measure the performance of *CUS* operations. The evaluation of the metrics of interest is based on these resulting *s.p.*s. We provide a conceptual representation of our simulation approach in Figure 6.

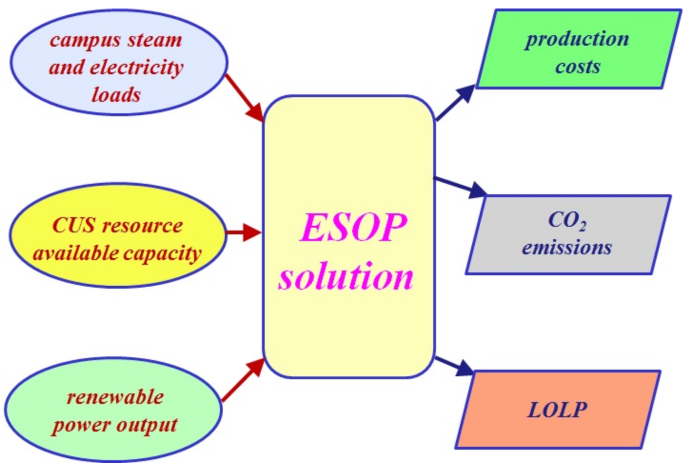

Fig. 6. *Conceptual structure of the simulation approach*

IV. Illustrative case study

We deploy the simulation approach twice to obtain the results of the *UIUC CUS* operations under the μg and the optimal operations of the current paradigm. The results provide useful insights into the quantification of the relative benefits of the μg concept application in terms of the economics, reliability and emission indices with respect to the *UIUC CUS* operations under the current and μg operations. We compare the *CUS* operational performance for the optimal operations of the current and the μg operational paradigm on the basis of the average daily cost of energy production in *dollars* as the metric for economics, average daily *LOLP* as the metric for reliability and average daily CO_2 emissions in *metric tons* as the metric of emissions. We point out that the comparative performance results obtained are consistent in a sense that the resource mix is held constant when *CUS* operational performance is compared under the two operational paradigms.

We limit our analysis to a single year with the 365 days in the year partitioned into four *seasons* of three months each and focus on the insights into the nature of the results obtained. Therefore, the four *seasons* are *Jan–Mar*, *Apr–Jun*, *Jul–Sep* and *Oct–Dec* respectively. Taking into account the seasonal effects, maintenance schedules for the *APP* conventional resources and the academic calendar of the university, we select 32 representative days, 8 for each *season* in the year as the simulation periods to quantify the *CUS* operational performance under optimal operations of the current and μg operational paradigm in each case. We also note that all graphs in both the case studies are done over the "average day in a season in the year", for which the hourly values are averaged over all the representative days, with weights equal to the number of actual days represented by each representative day.

The study performed uses the electricity and steam load data for the year 2014 and 2015 provided by the *UIUC F&S*. The annual peak electricity load is 81 *MW* and the annual *CUS* peak steam load is about 553 *klb*. The electricity loads during the *Jul–Sep* months are higher than the other seasons in an year and the steam load are higher for the *Jan–Mar* months. The total nameplate capacity of the conventional electricity generation resources is about 89 *MW*. The *CUS* can further buy up to 60 *MW* of electricity on the *MISO* wholesale electricity market. The maximum steam that the *APP* resources can produce is 624 *klb*. Each electricity conventional generator is modeled as a two state unit with its own failure/recovery rate. The steam producing resources are also modeled as two state units with their own failure/recovery rates. In modeling conventional electricity and steam generation units, we specifically take into account the maintenance schedules. The maintenance typically happens during September and October. The tie line connecting the *UIUC CUS* electricity grid to the *Ameren DN* is also modeled as a two state unit. For the *PSSF* case, we incorporate the *UIUC PSSF* with a name plate capacity of 4.68 *MW*. We use the *UIUC PSSF* data for the year 2016. All the data used in the simulation is summarized in the form of tables in [20].

There are certain assumptions with respect to the study performed. The studies performed are of a backcasting nature. As such, we assume perfect information about the forecasts since we make use of historical data in our simulation. To transform the current paradigm into either the optimal operations of the current or the μg operational paradigm some, asset investments would have to be made and we assume such investments and do not consider them in the comparative quantitative analysis.

We now discuss the comparative performance of the *UIUC CUS* under the two operational paradigms. To carry out a consistent comparative performance assessment of the optimal operations of current and μg operational paradigm in the operations time frame, we assume that the *PSSF* is owned by the *UIUC CUS* and the *CUS* does not pay money to the company *Phoenix Solar Inc.* for each *kW* of *PSSF* output consumed.

In Figure 7, we show the average daily cost of production of energy in *CUS* under different operational paradigms. We observe that the optimal operations of the *UIUC CUS* reduce the average daily cost of production for an average day in any season from the current operations under the given assumptions; there is not a significant difference between the average daily cost of production under the μg operational paradigm and the optimal operations of current operational paradigm. The average daily cost of production of energy in the *CUS* is highest for a typical day in *Jul–Sep*, closely followed by the average daily cost of production of energy in *CUS* for a typical day in *Jan–Mar*.

TABLE I
PERCENTAGE REDUCTION IN PRODUCTION COSTS UNDER OPTIMAL OPERATIONS OF THE CURRENT AND μg PARADIGM FROM CURRENT OPERATIONS FOR THE *PSSF* CASE

average day in	***% reduction in production costs under μg operations from current paradigm***
Jan-Mar	3.95 %
Apr-Jun	3.21 %
Jul-Sep	2.98 %
Oct-Dec	3.48 %

We present the percentage reduction of the average daily cost of production of energy under the μg operational paradigm from the current operational paradigm for an average day in each of the seasons in Table I.

The percentage reduction in production costs from the current to the μg operations paradigm would translate to over 979 *thousand $* annually.

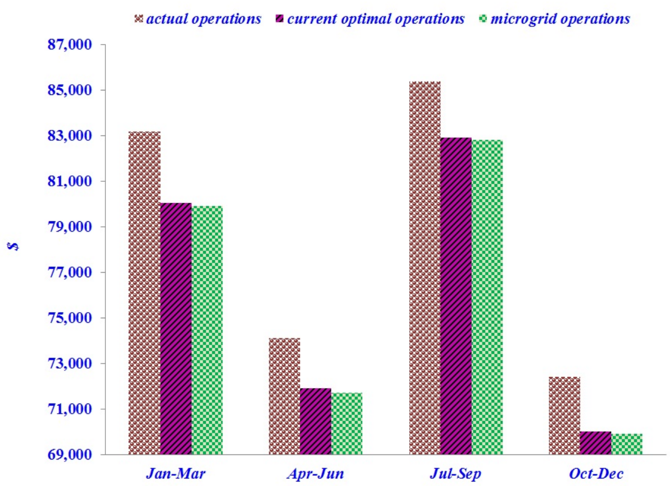

Fig. 7. *Average daily energy production costs*

In Figure 8, we show the average daily *LOLP* under two operational paradigms. The μg operational paradigm definitely brings an improvement in reliability metrics compared to the optimal operations of the current paradigm. Among the various months, the average daily *LOLP* is highest for a typical day in *Jul–Sep*, closely followed by the average daily *LOLP* for a typical day in *Oct–Dec* due to higher summer electricity loads.

In Figure 9, we show the average daily CO_2 emissions in the *CUS* under the two operational paradigms. There is an insignificant difference in terms of the average daily CO_2 emissions between the optimal operations of current and μg operational paradigm. Since the *CUS* steam load is higher for a typical day in *Jan–Mar* and *Oct–Dec*, and during such months the *CUS* depends on the *APP* units, the average daily CO_2 emissions are higher for a typical day in *Jan–Mar* and *Oct–Dec* as compared to the emissions for a typical day in *Apr–Jun*

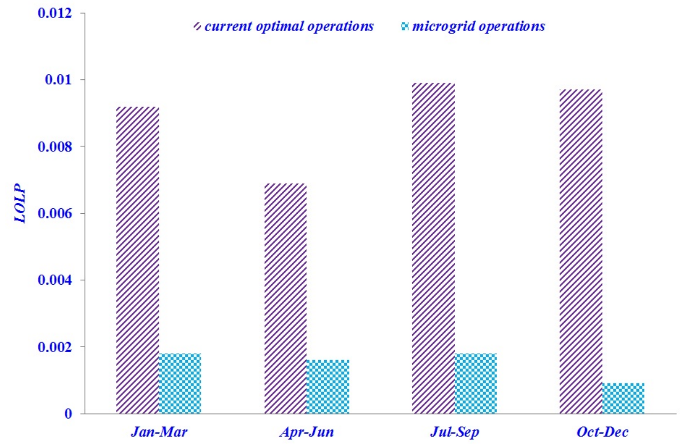

Fig. 8. *Average daily LOLP*

and *Jul–Sep*.

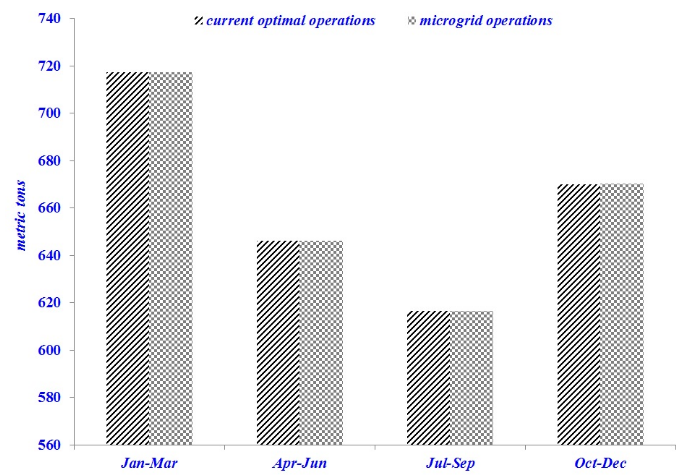

Fig. 9. *Average daily CO_2 emissions*

The improvements in the *CUS* operational performance are seen when the reliability and economic metrics are compared for both the paradigms. The improvements shown by the μg operational paradigm over the current operational paradigm are important but that analysis is done under the assumption that the perfect knowledge of the forecasts is available given the backcasting nature of the studies; additional costs that allow the system to operate under the μg operational paradigm are not accounted for in the quantitative analysis. The analysis gives some insights as to how the *UIUC CUS* would improve its operational performance when operated in the μg operational paradigm *versus* the current operational paradigm and would help making informed decisions on investing on the μg concept application to the *UIUC CUS*. *CUS* has some unique characteristics in terms of inter–dependencies between the steam and electricity sources. For the *UIUC CUS*, the steam load is as much a driver as the electricity load for the nature of the scheduling decisions. Due to the stringent thermal load in the *UIUC CUS*, there is not much leeway for the μg operational paradigm to show major improvements when compared to the optimal operations of the current paradigm for the *UIUC CUS*. There is no practical way to buy steam like we buy electricity in the wholesale electricity market. The fact that we do not have a practical alternative to meeting the *CUS* steam demand other than generating it on campus does not help either, as provision of steam demand becomes a key driver for the *UIUC CUS* scheduling decisions. Similarly, it is not practical for the *CUS* to be completely transformed into a purely renewable system as the *CUS* must have generation resources to meet the steam load.

V. Conclusion

We gain important insights about the *UIUC CUS* and the μg concept application from the quantitative comparison of *UIUC CUS* operational performance as is *versus* as a μg. A key observation made is that the extent of the benefits of the μg concept application to a power system attained would depend on the characteristics of the system as well as the location of the system in a geographical footprint of the bulk power system. In case of the *UIUC CUS*, the μg operational paradigm provides small improvements to the *UIUC CUS* economic and reliability operational performance when compared to the optimal operations of the current paradigm due to the salient features of the *UIUC CUS*. An important step in the future is to apply the approach to other power systems and observe the extent to which the benefits of the μg concept application are realized. For a system where the supply of electricity from the upstream grid is not reliable, the μg operational paradigm may show more improvements in the economics, reliability and emissions of system operations when compared to the optimal operations of the current paradigm. This may be due to the fact that under the μg operational paradigm, the system will maintain the continuity of electricity supply for longer duration, thus saving on the start–up/shut–down costs of the system resources. Furthermore, it would also be interesting to deploy this methodology on different configurations of the μgs and compare them on the basis of the metrics of interest to decide on a more appropriate configuration to invest upon.

The μg implementation progress to date pushes the creation of sustainable paths to meet each nations energy needs, veering it towards energy independence. However, to proceed with the large–scale deployment of μgs in distribution grids so as to effectively harness their utilization, there is a need to understand quantitatively the extent to which μg benefits realize to a power system. This paper demonstrates the application of a comprehensive simulation methodology developed that can quantitatively demonstrate the improvements in the reliability, economics and emissions attained by the μg concept application to a power system such as the *UIUC CUS*. The simulation–based approach is an important new addition to the existing literature for a comprehensive quantification of μg benefits and the *UIUC CUS* simulation results provide a good example of the limits of the μg concept benefits.

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