Provisional Microgrid Planning

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***Abstract*— The optimal planning problem of provisional microgrids, as a new class of microgrids, is investigated in this paper. Unlike traditional microgrids, provisional microgrids do not possess the islanding capability and are dependent on one or more electrically connected microgrids, called coupled microgrids, for islanding purposes. Provisional microgrids can be considered as enablers of rapid integration of renewable energy resources in distribution networks while at the same time providing economic benefits for local consumers and environmental benefits for the entire system. The provisional microgrid planning problem is defined and formulated in this paper, considering anticipated interactions between the provisional microgrid, the coupled microgrid, and the utility grid, during grid-connected and islanded modes. Robust optimization is used to efficiently consider physical and financial uncertainties in the problem. Numerical simulations study a test provisional microgrid for exploring its merits, as well as demonstrating its benefits when compared to deployment of a traditional microgrid.**

***Index Terms*— Provisional microgrid, planning, islanded operation, renewable distributed generator, uncertainty, robust optimization.**

NOMENCLATURE

Indices

b	Index for hour
h	Index for day
i	Index for DERs
t	Index for year

Sets

W	Set of renewable energy resources
$\mathrm{P}, \mathrm{P}_1, \mathrm{P}_2$	Set of primal variables
U	Set of uncertain parameters

Parameters

CC	Annualized investment cost of generating units
d	Discount rate
D	Load demand
$P^{\max}$	Rated power of DERs
$P_{CM}^{\max}$	Flow limit between the provisional microgrid and the coupled microgrid
$P_{M}^{\max}$	Flow limit between the provisional microgrid and the utility grid
κ	Coefficient of present-worth value
ρ_{CM}	Energy purchase price from the coupled microgrid
ρ_{M}	Energy purchase price from the utility grid
u	Binary islanding variable (1 if grid-connected, 0 if islanded)
v	Value of lost load (VOLL)

Variables

LS	Load curtailment
P	DER output power
P_{CM}	Coupled microgrid power
P_{M}	Utility grid power
PC	Total planning cost
Q	Total annual operation cost
x	DER investment state (1 if installed, 0 otherwise)
ϑ	Dual variable
Λ	Projected operation cost in the investment problem

I. INTRODUCTION

MICROGRIDS are becoming viable alternatives to centralized generation and bulk transmission of power by offering a localized power generation, regulation, and consumption. There are a diverse set of benefits stemmed from microgrids, including but not limited to, enhanced reliability by enabling self-healing, enhanced resiliency by responding to extreme events and utility grid supply interruptions, increased efficiency by reducing losses, deferred transmission and distribution upgrades by providing a local supply of loads, and enhanced integration of responsive and adjustable loads. Enhancing a rapid integration of renewable energy resources, however, cannot be considered as one of the benefits of microgrids. As defined by the U.S. Department of Energy, a microgrid is "a group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes" [1]. Based on this definition, a microgrid must be able to operate in islanded mode to seamlessly supply local loads. The integration of renewable energy resources, however, would not help with this requirement as renewable energy resources are uncontrollable, hence, microgrid developers would prefer to utilize dispatchable energy resources, such as CHPs, for microgrid local generation rather than renewable energy resources.

On the other hand, the large-scale centralized integration of renewable energy resources is on the rise to reduce generation

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related greenhouse gas emissions, address environmental concerns, and ensure energy security and sustainability by the diversification of energy resources. Broader integration of renewable energy is specifically targeted in the United States by state and governmental mandates which aim at enforcing the environmental agenda by mitigating greenhouse gasses generated by exhaustion of fossil fuels and combat climate change. The Renewable Portfolio Standards (RPS) is a good example of these mandates which demands the electric power providers to supply a specific amount of electric power from renewable energy resources. A widespread deployment of these viable resources, however, is subject to several significant burdens including financial and technical. From a financial perspective, the capital cost of renewable energy resources is much higher than traditional energy resources. Although tied with insignificant operation costs, the large capital cost of these resources and the associated long return on investment is considered as a major drawback. The financial issue, however, is becoming less of a concern as the technological advances are causing considerable price drops in renewable technologies. Moreover, a variety of policies and regulations are applied by the states and governments to support investments on renewable energy resources. Some of examples in the Unites States include public benefit funds for renewable energy (which are obtained by levying small taxes on electricity rates), output-based environmental regulations (which ordain emission limits in order to encourage electric producers to increase efficiency and control air pollution), net energy metering (to allow prosumers to sell their excess generation back to the utility for reducing energy payments as well as transmission and distribution charges), feed-in tariffs (that encourage renewable energy development by requiring electric utilities to make long-term payments for the power fed by renewable energy developers onto the utility grid), property assessed clean energy (in which the cost of renewable energy installations or increasing energy efficiency is refunded to residential properties instead of individual borrowers, so encouraging property owners to invest in renewable energy improvements), and other financial incentives (including grants, loans, rebates, and tax credits that are offered to encourage the renewable energy deployment) [2]. From a technical perspective, there are significant drawbacks in integration of renewable energy resources to the electric power system. Major sources of renewable energy, i.e., wind and solar, are significantly dependent on meteorological factors. These resources are highly unpredictable and cause considerable variability in power generation. Two major characteristics of renewable generation are intermittency (i.e., not always available - such as solar generation which is not available during nighttime), and volatility (i.e., constant fluctuations from seconds to minutes to hours - such as wind generation that depends on the speed and availability of wind, or solar generation which could radically change as the cloud cover changes). To enable an efficient integration of renewable energy resources, system planners have traditionally considered backup generation for smoothing out the generation variability. Backup generations typically offer a fast response to generation changes; common examples are fast-response gas units, hydro units, demand management, and energy storage systems. In these cases, there is a chance that the true value of the backup generation installation cannot be achieved, since the backup is typically used for the sole purpose of coordinating the renewable generation. Hence, its cost will be added to the already large capital cost of the renewable energy resource and further question the economic viability of the deployment. Another major issue that results from the generation variability of these resources is that the interruption in power supply from the utility grid cannot be fully compensated by these resources as the generation cannot be controlled. In other words, these resources, if deployed stand-alone, cannot ensure generation reliability. A viable alternative to backup generation, while at the same guaranteeing reliability, is to deploy microgrids.

Combining these two issues, it can be stated that: 1) Microgrids could play a viable role in ensuring a rapid and widespread integration of renewable energy resources in distribution networks by providing a flexible backup generation and addressing the prevailing technical constraints, and 2) Microgrid developers are not in favor of renewable energy resources since these resources are associated with higher capital costs and also cannot be used for islanding purposes to reliably supply critical loads when the supply of power from the utility grid is interrupted. The second point is a more decisive factor in microgrid deployments as it can be seen in current microgrid deployments. Islanding is the most salient feature of the microgrids which represents the microgrid capability to be disconnected from the main grid in case of upstream disturbances or voltage fluctuations [3]-[7]. This capability is ensured by the utilization of dispatchable distributed generators (DGs), energy storage, and demand management, which together could be scheduled to supply the peak critical load when disconnected from the utility grid [8].

To address this conflict, i.e., to benefit from microgrid to enable rapid integration of renewable energy resources, the concept of provisional microgrids has been proposed [9]. Provisional microgrids are defined as "a group of interconnected loads and renewable DGs with clearly defined electrical boundaries that acts as a single entity with respect to the grid but requires additional generation from electrically connected microgrids to enable it to operate in island modes". Based on this definition, provisional microgrids could utilize a high percentage of renewable energy resources without concerning about islanding requirements. When islanding is needed, the provisional microgrid would be disconnected from the utility grid and rely on its own generation, as well as generation of the coupled microgrid, to supply local loads. Provisional microgrids aim at achieving the objectives of addressing the economic and reliability needs of electricity consumers with less critical and sensitive loads, procuring distribution network flexibility offered by existing microgrids, and ensuring a rapid and widespread deployment of renewable energy resources in distribution networks. The concept of provisional microgrids can also be looked at from the prosumers' perspective. Prosumers, i.e., electricity consumers which are equipped with DGs and can partially supply their electricity needs, are rapidly increasing in the Unites States and around the world. These prosumers primarily deploy renewable DGs which although can be helpful in reducing the electricity payments, their variable nature prevents reliability improvements. However, if a microgrid is available and electrically connected to the prosumer, e.g. in the same distribution feeder, the prosumer can rely on a supply of power from the microgrid in case of utility grid supply interruption, and therefore, improve its reliability. In other words, prosumers can be elevated to the status of provisional microgrids if they can make a connection to an existing microgrid to purchase power during islanded operation and also utilize a master controller to monitor and control the power exchange with the coupled microgrid.

Provisional microgrids could be further considered as extensions to microgrid clusters. There are several studies regarding microgrid clusters in the literature from different perspectives, including economic analysis, cooperative scheduling, and efficient control. Economic benefits of microgrid clusters are discussed in [10] and [11] where it is shown that their operation leads to reduction in emissions and end user cost while addressing the load growth. Microgrid clusters enable an efficient energy trading by allowing cooperation. The study in [12] formulates a coalitional game between a number of microgrids to study novel cooperative strategies in microgrid clusters. Simulation results show a reduction in terms of the average power losses relative to the non-cooperative case. An analysis of price competition among interconnected microgrids is presented in [13] using the game theory framework, which explicitly computes Nash Equilibrium and shows its uniqueness. The study in [14] addresses the case where two microgrids are isolated from the utility grid but can exchange energy with each other in a peer-to-peer manner aiming to minimize the total cost resulting from energy generation and transfer, while each microgrid satisfies its local power demand. The control of the microgrid clusters is another important topic of study. In [15] a microgrid cluster control system is proposed and implemented using multi-agent systems for communication and control among a number of adjacent microgrids. The study in [16] presents a novel microgrid cluster with a distributed control oriented hierarchical system and distributed multi-agent system architecture. Agents include the microgrid cluster management, microgrid control, and local agents. A multi-agent system is a network system composed of a number of loosely coupled agents. These agents are physically or logically dispersed, and have some distinct characteristics, including distributed data, an asynchronous or simultaneous process of computation, lack of information and capability of individual problem solving, and interaction and cooperation with other agents to improve their problem solving capability. In [17] the control of microgrid clusters is performed in three levels: local microsource and load controller, microgrid central controller, and distribution management system. Control of this system is done by a central autonomous management controller, which serves as an interface to the distribution management system. In [18] a hierarchical and decentralized scheme for coordinated voltage support and frequency control, as well as for state estimation for microgrid clusters, is proposed. Fuzzy state estimation and microgrid cluster state estimation are further proposed in [17] and [19]. In [19] control functionality to manage micro-generation in microgrid clusters is proposed considering active loads and energy storage, subject to different constraints. Discussions on microgrid clusters consider two or more microgrids which are capable of operating in the islanded mode without the need to purchase power from connected microgrids. In this case, power exchanges are commonly performed to improve economics and control rather than ensuring a seamless islanding. The concept of provisional microgrids was proposed in [9] accompanied by detailed discussions on its optimal scheduling problem. This paper builds on that work to show that in addition to an economic operation, provisional microgrids could be considered as viable alternatives compared to microgrids from a least-cost planning perspective.

The rest of the paper is organized as follows. Section II reviews the concept of provisional microgrids and further outlines the planning model and decisive factors in the planning problem. Section III formulates the planning problem while Section IV discusses the application of robust optimization to solve the planning problem. Section V performs numerical studies on a test system. Discussion on the features of the proposed model and concluding remarks are provided in Sections VI and VII, respectively.

II. PLANNING PROBLEM MODEL OUTLINE

Provisional microgrids are similar to microgrids as their electrical boundaries are clearly defined and a master controller operates and controls available resources. Unlike microgrids, however, provisional microgrids do not have the ability to be islanded on their own. Provisional microgrids are dependent on one or more electrically connected microgrids, called coupled microgrids, for operation in the islanded mode. Provisional microgrids could utilize a high percentage of renewable energy resources without concerning about islanding requirements. When islanding is needed, the provisional microgrid would be disconnected from the main grid distribution network and rely on its own generation, as well as generation from the coupled microgrid, to supply local loads. It should further be assumed that the loads within the provisional microgrid are not critical. The connection to the coupled microgrid would provide the required flexibility to coordinate variable generation if needed, and also the unused capacity of the coupled microgrid would be used in islanding incidents to ensure adequate supply of local loads.

In the grid-connected mode, the provisional microgrid generates power by coordinating available resources and interacts with the utility grid for power transfer to supply local loads, while in the islanded mode it disconnects from the utility grid distribution network and transfers power with the coupled microgrid. The provisional microgrid and the coupled microgrid would operate simultaneously in the islanded mode in response to utility grid failures and/or voltage fluctuations, where it is assumed that the connection between the provisional microgrid and the coupled microgrid will be maintained during islanding. The provisional microgrid would further rely on the coupled microgrid for frequency regulation and voltage control. The coupled microgrid would treat the provisional microgrid as a load, similar to how it treats its local loads. There are not any controllable devices in the provisional microgrid, so a coordinated control between two microgrids would not seem necessary. Significant economic and reliability benefits, which will stem from the power transfer, are momentous drivers in maintaining the connection between the provisional microgrid and the coupled microgrid in islanded mode. The coupled microgrid would benefit by selling its excess generation to the provisional microgrid and the provisional microgrid could reliably supply its local loads, reduce load curtailment, and increase operational reliability. Although it is assumed that provisional microgrid loads are not critical, this capability would prevent undesired load curtailments.

Fig. 1 depicts the provisional and coupled microgrids power exchanges during grid-connected and islanded modes. Assuming that both microgrids are connected to the same upstream HV substation, i.e., the market price for both microgrids is the same, and also microgrids are connected to the utility grid with adequately large line capacities that can handle the maximum local load, it can be observed that there would be no power exchange between the microgrids during the grid-connected mode. To clarify the issue, suppose that the market price is lower than the price of power transfer from the coupled microgrid to the provisional microgrid. In this case, the provisional microgrid would prefer to purchase power from the utility grid rather than the coupled microgrid. Also if it has excess generation, the coupled microgrid would not be interested in purchasing the power from the provisional microgrid, as it could be acquired from the utility grid at a lower price. The same observation is valid when the market price is higher than the price of power transfer from the coupled microgrid. In this case, the provisional microgrid would be willing to purchase power from the coupled microgrid, however, the coupled microgrid would sell its excess generation, if any, to the utility grid as it would result in a higher benefit. Considering these, there would be no power exchange between the provisional microgrid and the coupled microgrid in the grid-connected mode as it would reduce their individual economic benefits.

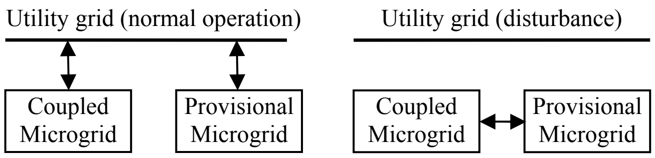

Fig. 1 Provisional microgrid operation during grid-connected (left) and islanded (right) operation modes

In most of the operating hours, the power transfer with the utility grid helps supply local loads. In minor and infrequent islanded hours, the power transfer with the coupled microgrid combined with the local generation enables supplying local loads. The coupled microgrid is designed to completely supply its critical loads at peak hours. Therefore, the coupled microgrid would normally have unused capacity in both grid-connected and islanded modes. The coupled microgrid excess generation, beyond its load, would help the provisional microgrid to supply local loads during islanded operation. If sufficient generation is not available to fully supply loads, the provisional microgrid will curtail some of its load to guarantee load-supply balance. The possibility of load curtailment must be considered in the provisional microgrid design process as the cost of reliability. A second approach, which will be more favorable for both microgrids, is to follow negotiated capacity and price values of power transfer during islanded modes. If the capacity and the price are negotiated, i.e., both microgrids agree beforehand on the maximum available power transfer as well as price per kWh of transfer during islanded modes, there would be no uncertainty for power exchange. The coupled microgrid benefits from this agreement as it would sell its excess generation to the provisional microgrid during islanded modes; the provisional microgrid benefits from this agreement as it would reduce load curtailments if adequate local generation is not available. This method is considered in this paper for provisional microgrid planning, where case studies are further performed to show the sensitivity of planning results to negotiated capacity and price values.

A multiple time-scale planning problem is proposed, comprising the provisional microgrid long-term investment (i.e., annual) and short-term operation (i.e., hourly). Any other scheduling resolution can be selected based on the developer's discretion without loss of generality in the proposed model. By the selection of an hourly scheduling, schedules are obtained based on hourly operation and also the islanding duration is considered as an integer multiple of one hour. Shorter time periods could be employed to more accurately capture rapid changes in load and renewable generation as well as shorter islanding durations. The selection of a proper time period for scheduling represents a tradeoff between the solution accuracy and the computation time. Shorter time periods would analyze more data and provide more accurate solutions while increasing computation requirements. Simultaneous consideration of annual investment with short-term operation follows the extensive work in power system dynamic planning, such as in [20]-[24].

III. PLANNING PROBLEM FORMULATION

The objective of the provisional microgrid planning problem is to minimize the total planning cost (1) subject to operational constraints (2)-(6). The total planning cost, here shown with *PC*, includes the renewable DG investment cost, provisional microgrid operation cost, and the cost of unserved energy. The planning problem is formulated as follows:

$$\begin{aligned} \underset{\mathrm{P}}{\text{minimize}}\, PC = &\sum_t \sum_i \kappa_t CC_{it} P_i^{\max} x_i \\ &+\sum_t \sum_h \sum_b \kappa_t \rho_{CM,bht} P_{CM,bht} \\ &+\sum_t \sum_h \sum_b \kappa_t \rho_{M,bht} P_{M,bht} \\ &+\sum_t \sum_h \sum_b \kappa_t v_{bht} LS_{bht} \end{aligned} \tag{1}$$

Subject to:

$$\sum_i P_{ibht} + P_{M,bht} + P_{CM,bht} + LS_{bht} = D_{bht} \qquad \forall b, \forall h, \forall t \tag{2}$$

$$-P_M^{\max} u_{bht} \le P_{M,bht} \le P_M^{\max} u_{bht} \qquad \forall b, \forall h, \forall t \tag{3}$$

$$-P_{CM,bht}^{\max}(1-u_{bht}) \le P_{CM,bht} \le P_{CM,bht}^{\max}(1-u_{bht}) \, \forall b, \forall h, \forall t \tag{4}$$

$$P_{ibht} = \hat{P}_{ibht} x_i \qquad \forall i, \forall b, \forall h, \forall t \tag{5}$$

$$0 \le LS_{bht} \le D_{bht} \qquad \forall b, \forall h, \forall t \tag{6}$$

The objective is minimized over the set of primal variables P, where P={*x*, P_{CM}, P_M, *LS*}. The investment cost of renewable DGs is a function of their generating capacity. It is assumed that the operation cost associated with renewable DGs is negligible, thus the microgrid operation cost includes the cost of energy purchase from the utility grid plus the cost of energy purchase from the coupled microgrid. The cost of energy purchase is defined as the amount of purchased energy times the associated price at the point of connection. A single-step price curve is considered for energy purchase from the coupled microgrid. The utility grid power P_M would be negative if the provisional microgrid is exporting its excess power to the utility grid (paid at market price). The coupled microgrid power P_{CM} would be negative if the provisional microgrid is exporting its excess power to the coupled microgrid (paid at the negotiated price). The cost of unserved energy, which represents the provisional microgrid reliability in supplying local loads, is defined as the load curtailment quantity times the value of lost load (VOLL). VOLL is the energy price for compensating curtailed consumers, which depends on several factors including the types of consumers, quantities and durations of curtailments, and the time of outages. A higher VOLL corresponds to more critical loads [25]-[26]. The objective is evaluated in terms of discounted costs, where discount rates are incorporated in the present-worth cost components, i.e., $\kappa_t = 1/(1+d)^{t-1}$. It should be considered that only renewable DGs are considered for installation in the provisional microgrid, therefore, there would be no installation and operation cost associated with dispatchable DGs and the energy storage in the objective. The investment cost is defined annually while operation costs are calculated hourly in the planning horizon.

The power balance equation (2) ensures that the provisional microgrid load will be supplied by the local generation, the power from the utility grid, and the power from the coupled microgrid. A load curtailment variable is added to the load balance equation to compensate generation shortages in islanded modes. The load curtailment will be zero during grid-connected operation as it can be assumed that adequate power can be supplied from the utility grid to fully supply local loads. The provisional microgrid power transfer with the utility grid in the grid-connected mode is limited by the flow limit of the associated connecting line (3), and will be zero in islanded mode, where *u*=0. The provisional microgrid power transfer with the coupled microgrid will be restricted by negotiated capacity limits during islanded modes (4), and will be zero during grid-connected mode, where *u*=1. The renewable generation is obtained based on a forecast, and will be set to zero if the associated renewable DG is not selected for installation (5). Finally, the hourly load curtailment is considered nonnegative and restricted to participating loads (6). The modeling of the provisional microgrid power transfer with the utility grid and the coupled microgrid are consistent with discussions in Section II.

IV. ROBUST OPTIMIZATION

The proposed provisional microgrid planning problem is subject to several uncertainties, i.e., factors which are having a major influence on planning decisions but are not under control of the microgrid developer or cannot be predicted with certainty. Forecasts associated with loads, market prices, nondispatchable generation, as well as islanding incidents can be considered as prevailing uncertainties in the planning problem. Moreover, the information associated with the coupled microgrid could be uncertain which includes the available unused capacity in islanded operation and the generation price. However, as discussed, it is assumed that the information from the coupled microgrid will be negotiated and known in advance, hence removing the associated uncertainty. To efficiently manage uncertainties, a robust optimization method will be adopted [27]-[31]. Fig. 2 depicts the flowchart of the proposed provisional microgrid planning model where the original planning problem is decomposed to a master problem and a subproblem.

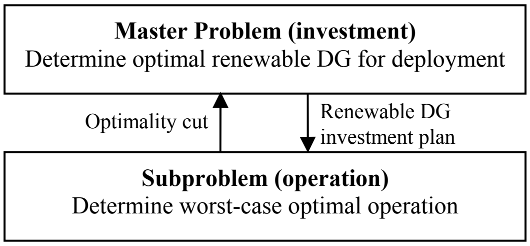

Fig. 2 Proposed provisional microgrid planning model

The master problem, which is an investment problem, determines the least-cost candidate renewable DGs to be installed, and is formulated as follows:

$$\underset{\mathrm{P}_1}{\text{minimize}}\, IC = \sum_t \sum_i \kappa_t CC_{it} P_i^{\max} x_i + \sum_t \kappa_t \Lambda_t \qquad (7)$$

Subject to:

$$\Lambda_t \ge \hat{Q}_t + \sum_h \sum_b \sum_i \vartheta_{ibht} \hat{P}_{ibht} (x_i - \hat{x}_i) \qquad (8)$$

The objective is minimized over the set of primal variables $\mathrm{P}_1=\{x\}$, and is subject to the optimality cut (8) formed in the subproblem. Q_t is the calculated objective value of the subproblem, i.e., (9). The optimality cut indicates that the solution of the revised investment plan can lead to a more economical solution in the subproblem. The subproblem, which deals with optimal operation of the provisional microgrid, uses the obtained plan to find the optimal interactions with the utility grid and the coupled microgrid while considering physical and financial uncertainties. The objective of the subproblem comprises the provisional microgrid operation cost and the cost of unserved energy (9). A worst-case analysis is performed to determine a robust solution against uncertainties, where the objective is minimized over the set of primal variables $\mathrm{P}_2=\{P_{CM}, P_M, LS\}$ and maximized over the set of uncertain parameters $\mathrm{U}=\{P, D, u\}$. The subproblem for each planning year t is defined as follows:

$$\begin{aligned} \underset{\mathrm{U}}{\text{maximize}}\,\underset{\mathrm{P}_2}{\min}\, Q_t = & \sum_h \sum_b \kappa_t \rho_{CM,bht} P_{CM,bht} \\ & + \sum_h \sum_b \kappa_t \rho_{M,bht} P_{M,bht} \qquad (9) \\ & + \sum_h \sum_b \kappa_t v_{bht} LS_{bht} \end{aligned}$$

Subject to:

$$P_{ibht} = \hat{P}_{ibht} \hat{x}_i \quad \perp \quad \vartheta_{ibht} \qquad \forall i, \forall b, \forall h \qquad (10)$$

and (2)-(6).

Constraint (10) considers the impact of the investment state determined in the master problem on renewable generation. If x=0, the associated generation will be set to zero, and if x=1, the associated generation will be equal to the forecasted value. This constraint further helps determine the dual multiplier required for forming the optimality cut.

Polyhedral uncertainty sets are considered in which uncertain parameters would choose one of extreme points of the associated uncertainty interval. The solution of the subproblem is further used to examine the convergence, which is based on the proximity of a lower bound (calculated in the master problem) and an upper bound (calculated in the subproblem). If not converged, the optimality cut (8) will be generated in the subproblem and sent back to the master problem for revising current planning decisions. Once converged, the plan is considered final. The proposed robust optimization follows the formulation in [32], while the coupled microgrid power transfer is added as a new variable.

V. NUMERICAL SIMULATIONS

A provisional microgrid is to be installed for a group of electricity consumers with a peak annual load demand of 8.5 MW. The set of candidates includes two renewable DGs including one aggregated solar unit and one aggregated wind unit. The rated power for both renewable DGs is considered 2 MW, with annualized investment costs of \$120,000/MW and \$180,000/MW for the solar unit and the wind unit, respectively. The load, variable renewable generation, and market price are forecasted based on historical data [33]-[34]. Nine hours of islanding per year is considered. The impact of islanding hours on planning results is further investigated in case studies. The planning horizon is 20 years. The problem is implemented on a 2.4-GHz personal computer using CPLEX 12.1 [35]. There is no limit on the power transfer with the utility grid, where the capacity limit of the line connecting the provisional microgrid to the utility grid is considered to be adequately large to handle any power transfer. The power transfer limit with the coupled microgrid during islanded mode is initially considered 1 MW with a negotiated price of \$90/MWh. Following cases are studied with a focus on the provisional microgrid planning based on a variety of decisive factors:

Case 1: Base case provisional microgrid planning
Case 2: Impact of the coupled microgrid power transfer capacity and price
Case 3: Impact of the rated power of candidates
Case 4: Impact of the number of islanding hours

Case 1: Base case provisional microgrid planning

The provisional microgrid planning problem is solved considering uncertainties in hourly load, renewable generation, and market price forecasts. A ±10 uncertainty in load forecasts and ±20 uncertainty in renewable generation and market price forecasts is considered. The limit on uncertainty option for load and renewable generation is considered 1000 hours/year, while this limit for the market price is set at 2000 hours/year. The islanding is limited to nine hours in each planning year.

The provisional microgrid planning solution would install both renewable DGs 1 and 2. The total planning cost is \$40,607,816, with a cost breakdown of \$10,007,077 for the investment, \$27,821,299 energy purchase from the utility grid, \$13,509 energy purchase from the coupled microgrid, and \$2,765,930 as the cost of unserved energy resulted from load curtailments. The cost of purchasing energy from the utility grid in case the provisional microgrid was not deployed, hence eliminating the energy purchase from the coupled microgrid, would be \$43,124,190 which is more than 6% larger than the total provisional microgrid planning cost. The difference in cost indicates that the provisional microgrid deployment is economical and the renewable DG investments will be recompensed from revenues. This solution is further compared with the case of a microgrid deployment as studied in [32]. The total planning cost of the microgrid deployment is \$42,451,534, which is larger than that of the provisional microgrid. This comparison clearly demonstrates the economic viability of the provisional microgrid when compared to the microgrid deployment or no development at all. When comparing to the microgrid development, some additional issues can be taken into consideration: i) The cost of unserved energy (which represents the provisional microgrid reliability in supplying local loads) is considered in the planning objective to ensure that the issue of reliability is quantified and considered in the planning problem. Hence, customers would not necessarily switch to a microgrid only because load curtailments will be lower; ii) The microgrid planning cost obtained from [32] only includes the cost of DER installation and microgrid operation. However, microgrids would require extensive additional investments for upgrading the microgrid distribution network and deploying a viable and sophisticated master controller to efficiently control and operate all DERs. These investments could potentially add additional costs and complexity in deployment and operation of microgrids, hence making the provisional microgrid a more suitable alternative for customers who are not willing to encounter that level of investment and complexity; iii) Similar input data is used in this study for both microgrid and provisional microgrid deployments, including similar VOLL. Since the provisional microgrid is deployed in areas with less critical loads, a smaller VOLL should be considered, hence reducing the total planning cost of the provisional microgrid deployment and further demonstrating its economic viability. Table I summarizes the costs associated with the planning of the microgrid, obtained from [32], and the provisional microgrid. From a generation mix perspective, the provisional microgrid deploys 100% renewable generation, compared to the microgrid which relies on only 16% of renewable generation and the rest will be based on dispatchable thermal units.

TABLE I
COMPARISON OF RESULTS BETWEEN MICROGRID AND PROVISIONAL MICROGRID DEPLOYMENTS

Installation Type	Planning Cost Breakdown ($)			
	Investment	Operation	Unserved	Total
Microgrid [32]	17,012,031	25,439,503	0	42,451,534
Provisional Microgrid	10,007,077	27,834,809	2,765,930	40,607,816

Case 2: Impact of the coupled microgrid power transfer capacity and price

The impact of the coupled microgrid power transfer capacity and price on the provisional microgrid planning results are further studied. The power transfer capacity is changed from 0 MW to 2 MW with a step of 0.5 MW. The VOLL is reduced to \$2000/MWh to represent less critical loads within the provisional microgrid. The provisional microgrid planning solution would install the renewable DG 1, i.e., the solar unit. Increasing the power transfer capacity with the coupled microgrid would not change the investment plan but would reduce the planning cost. The reduction in the planning cost is due to the reduced cost of unserved energy. As the transfer capacity increases the provisional microgrid would be able to purchase additional energy from the coupled microgrid during islanded hours, hence the load curtailment, and consequently the cost of unserved energy, would drop. Further decrease in the planning cost, however, would not occur for transfer capacities more than 3.77 MW since the load would be fully supplied during islanded hours and the cost of unserved energy would be zero.

The sensitivity analysis with respect to the power transfer price shows that independent of the price, the provisional microgrid would purchase power, up to the transfer capacity, at all islanded hours from the coupled microgrid. This result is obvious as it would be always more beneficial to purchase power from the coupled microgrid than to curtail loads. The economic benefit is obtained because of the lower price of the coupled microgrid compared to VOLL. Evidently, if the VOLL is less than the coupled microgrid transfer price, it would be more beneficial to curtail loads than to purchase the relatively expensive power from the coupled microgrid.

Case 3: Impact of the rated power of candidates

In this case the sensitivity of the planning cost with respect to the rated power is studied. In the proposed provisional microgrid planning problem, the rated power of candidate renewable DGs is considered as an input to the problem. To consider a variety of values for rated power, the forecasted generation is normalized and then scaled up based on the rated power. The VOLL is considered to be \$2000/MWh in this case. Fig. 3 shows the results of the sensitivity analysis.

As the rated power increases, the investment cost will linearly increase while the cost of energy purchase from the utility grid will decrease in a nonlinear fashion. The cost of energy purchase from the coupled microgrid and the cost of unserved energy are almost the same in all cases as the number of islanding hours hasn't changed and also renewable generation in the islanded hours is very small. Thus, the planning cost as shown in Fig. 3 will be obtained, demonstrating the optimal renewable DG rated power of 1.8 MW.

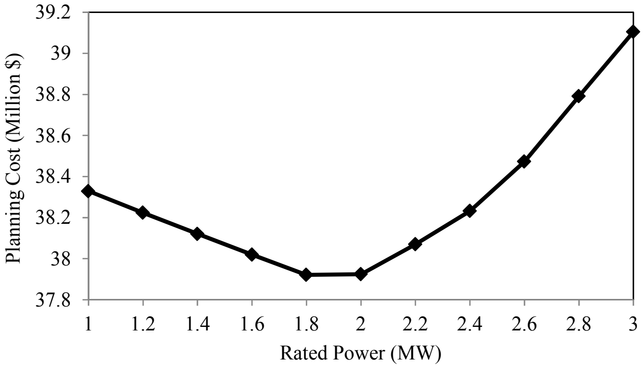

Fig. 3 Provisional microgrid planning cost as a function of the candidate DGs' rated power

Case 4: Impact of the number of islanding hours

The provisional microgrid planning problem is solved for a variety of islanding hours. As has been previously demonstrated in [32], the islanding always occurs at times that results in the lowest cost of unserved energy, i.e., when the load is at its lowest. As the number of islanding hours increases, the cost of energy purchase from the coupled microgrid as well as the cost of unserved energy increase, since these costs are directly associated with the islanded operation. The cost of energy purchase from the utility grid, on the other hand, slightly decreases since the power from the utility grid at islanding hours will be reduced to zero. In total, the provisional microgrid planning cost increases as the number of islanding hours increase. Considering this, the provisional microgrid is more economical when the number of islanding hours is limited, or in other words, the customer average interruption duration index (CAIDI) is low. This is a completely different result from the case of microgrids. The economic viability of microgrids is highly dependent on the number of islanding hours as a larger number would increase savings and reduce the payback time. This is mainly due to the high cost of unserved energy which will not occur when the microgrid is deployed. Furthermore, it is possible that for small values of islanding hours the microgrid installation would not be economical.

This study reveals a great difference between the microgrid and the provisional microgrid, i.e., their benefits in response to islanding hours. The microgrid, besides providing economic benefits by utilizing local resources, is a viable solution to consumers' reliability problems and would significantly reduce consumers' load curtailments. For the provisional microgrid, however, the case is different since it cannot be primarily used for reliability purposes.

VI. DISCUSSIONS

Provisional microgrids are defined to remove islanding considerations as part of the microgrid design and planning process, reduce the DER investment cost, and prevent underutilization of capital-intensive dispatchable units and underdeployment of renewable energy resources. Consequently, provisional microgrids could be considered as viable alternatives to guarantee a widespread and rapid deployment of renewable DGs in distribution networks. Specific features of the provisional microgrids, gained from the proposed provisional microgrid planning model and numerical studies, are listed as follows:

- Increasing renewable DG proliferation and positively impacting the environment: Compared to microgrids which primarily rely on a large percentage of dispatchable DGs for islanding purposes and include a small percentage of renewable DGs, the provisional microgrids could deploy 100% of their generation capacity based on renewable DGs, and further address environmental concerns by enabling large and distributed penetration of these emission-free resources in distribution networks.
- Economic benefits: Provisional microgrids could be potentially less expensive options to deploy when compared to microgrids for the same set of consumers, and could further guarantee a faster return on investment. The consumer VOLL and CAIDI will become decisive factors in this case since they could significantly change the planning results and alter the economic viability of the investments.
- Removing the need to enhance distribution network flexibility: Provisional microgrids will benefit from the available flexibility in distribution networks offered by existing microgrids, which would further operate as coupled microgrids and benefit from the electrical connection to the provisional microgrid. Thus, there would be no need for system operators to reinforce the distribution network flexibility by additional capital-intensive installations and system upgrades.
- Role of islanding hours: Despite microgrids which are viable options to address utility grid interruptions by switching to an islanded mode and reliably supplying local loads, provisional microgrids are not good options to be used for islanding purposes. In fact, provisional microgrids will become less attractive options as the number of islanding hours increases.

VII. CONCLUSIONS

The provisional microgrid planning problem was developed and formulated in this paper to show the significance of this novel concept and further enable progress toward the next generation of intelligent and sustainable integrated power grids. Provisional microgrids hold similar characteristics as microgrids, however, do not offer the islanding capability, hence allowing a larger deployment of renewable DGs. The provisional microgrid planning problem was solved for a variety of cases, showing the benefits and differences from a traditional microgrid deployment. It was shown that in comparison to microgrids, with a primary application of improving reliability for local customers and managing the ever increasing penetration of DERs, provisional microgrids would support the efficient deployment of renewable DGs in distribution networks by leveraging the available flexibility offered by already installed microgrids and benefiting from the capacity of coupled microgrids during the islanded operation. Therefore, the provisional microgrid can be considered as a viable concept to complement current research and development efforts on microgrids and further help advance microgrids to more practical energy systems.

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