Assessment of the Economic Potential of Microgrids for Reactive Power Supply

Appen, Jan von

2011-06-01

Assessment of the Economic Potential of Microgrids for Reactive Power Supply

Jan von Appen[1], Chris Marnay[2], Michael Stadler[2], Ilan Momber[3], David Klapp[4], and Alexander von Scheven[1]

1 Darmstadt University of Technology, Institute of Renewable Energies, Darmstadt, Germany
2 Lawrence Berkeley National Laboratory, Berkeley, CA, USA
3 UP Comillas, IIT, Madrid, Spain
4 American Electric Power, Dolan Technology Center, Columbus, OH, USA

**Environmental Energy
Technologies Division**

**paper presented at the ICPE2011-ECCE Asia
8th International Conference on Power Electronics -
ECCE Asia, Shilla Hotel, Jeju, Korea, 30 May - 3 June 2011**

http://eetd.lbl.gov/EA/EMP/emp-pubs.html

The work described in this paper was funded by the Office of Electricity Delivery and Energy Reliability's Smart Grids Program in the U.S. Department of Energy under Contract No. DE-AC02- 05CH11231. Von Appen (j.appen@stud.tu-darmstadt.de) and von Scheven's participation is funded by the TU Darmstadt.

Abstract -- **As power generation from variable distributed energy resources (DER) grows, energy flows in the network are changing, increasing the requirements for ancillary services, including voltage support. With the appropriate power converter, DER can provide ancillary services such as frequency control and voltage support. This paper outlines the economic potential of DERs coordinated in a microgrid to provide reactive power and voltage support at its point of common coupling. The DER Customer Adoption Model assesses the costs of providing reactive power, given local utility rules. Depending on the installed DER, the cost minimizing solution for supplying reactive power locally is chosen. Costs include the variable cost of the additional losses and the investment cost of appropriately over-sizing converters or purchasing capacitors. A case study of a large health care building in San Francisco is used to evaluate different revenue possibilities of creating an incentive for microgrids to provide reactive power.**

Index Terms – **microgrids, ancillary services, reactive power, and voltage support**

I. INTRODUCTION

Climate friendly electricity generation, energy policy and regulation are changing electricity supply. Smaller scale distributed generators and renewable energy resources are connected at distribution levels, making power flow increasingly bidirectional. This transforming infrastructure changes the distribution utility's and grid operator's responsibilities. In distribution, maintaining voltage is required to serve loads correctly, reduces losses, and improves capacity utilization delaying capacity upgrade investments. Maintaining system energy balance via frequency/power control and reactive power/voltage control are two of the two main ancillary services[1] required to guarantee stable and efficient operation. Traditionally, voltage support services have been performed either by central generators or dispersed equipment, such as capacitors [1,2].

The changing energy flow pattern and infrastructure raise the question of whether distributed energy resources (DER) could technically and economically provide ancillary services. This paper analyzes how microgrids, local clusters of DER, might participate in reactive power and voltage control provision.

Reactive power exists in every alternating current (AC) system, and is a result of phase shifting of the voltage and current curves. Reactive power Q and real power P are connected through the following relationship, where S is the apparent power [3]:

$$S^2 = P^2 + Q^2 \tag{1}$$

Most components in an electrical system act as an inductive/lagging or capacitive/leading source or sink of reactive power. Examples of inductive reactive power consumers are lines under load and devices with motors such as air conditioners or industrial equipment, while capacitors are reactive power sources.

Reactive power is consumed by certain loads together with real power, forcing operators to deliver both real and reactive power. The objective is to minimize the reactive power since it just contributes to losses. Reactive power flow causes real power losses, voltage decay, and poor equipment utilization in networks; therefore, supplying reactive power locally, usually using capacitors, is necessary. Controlling reactive power implies regulating the voltage, which is important for the proper operation of an electric system.

The underlying relationship between reactive power and voltage is the following: reactive power consumption leads to a voltage drop and vice-versa. Insufficient reactive power supply decreases the voltage, forcing the current to increase to serve the power required by loads, which leads to further reactive power consumption in the lines and higher voltage drop. Ultimately, a voltage collapse could occur, causing a system shut down. Maintaining the voltage within a certain range provides stability for the system and prevents voltage collapse, extreme examples of which were contributing causes of the US 1996 west coast and the 2003 east coast blackouts [4]. Furthermore voltage stability is necessary to prevent damage from overheating of motors and generators.

A recent Federal Energy Regulatory Commission (FERC) report on reactive power supply and consumption observes several problems and inefficiencies in current reactive power procurement at the transmission level. The lack of a price signal to incent participation in reactive power supply, missing incentives to coordinate reactive power supply between the different independent and regional system operators, as well as their failure to optimize reactive power dispatch locally have had significant impacts on grid reliability [4]. With generation moving to the distribution level, reactive power control is becoming a challenge in low voltage networks.

These examples point out the importance of well-functioning reactive power supply, and emphasize the need for a closer look at reactive power markets and microgrids' potential role. This paper explores the possibilities and circumstances under which microgrids might participate. Despite its impact on electricity supply security, the costs of local reactive power provision have traditionally been factored into most electricity tariffs as part of the distribution component, which typically accounts for 10 - 20% in the US[2][5]. In other words, capacitors have been considered as necessary hardware in the distribution network.

This paper is structured as follows: In section II the microgrid concept and DER technical reactive power supply capabilities are explained. Implications for incentives to participate in reactive power supply will be

---

The work described in this paper was funded by the Office of Electricity Delivery and Energy Reliability's Smart Grids Program in the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Author contact: Jan von Appen (jan.vonappen@iwes.fraunhofer.de).

[1] Ancillary services are inputs required for the operation of an electric power system and can be provided by the system operator, a local distribution utility, and/or by power system users.

[2] This includes the costs for other ancillary services like frequency-power-control

discussed in section III. Section IV describes the approach used to model reactive power supply using the DER Customer Adaption Model (DER-CAM) and assessing the costs and benefits of local reactive power provision by microgrids. In sections V and VI, a case study using DER-CAM derives implications for reactive power market participation by microgrids. This is followed by conclusions in section VII.

II. MICROGRIDS AND REACTIVE POWER SOURCES

A microgrid is a group of interconnected loads and DER within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode [6]. Combined heat production capable DER, such as internal combustion engines (ICE), microturbines (MT) or fuel cells (FC), coupled with small renewable energy generators such as photovoltaics (PV), solar thermal (ST) and storage technologies grouped into microgrids can offer a rich set of tools for providing the surrounding conventional network (macrogrid) with increased reliability, security of supply, flexibility, and improved power quality [7].

On the other hand reactive power sources can be divided into static and dynamic sources, referring to a source's ability to actively control reactive power output [8]. This paper distinguishes between conventional reactive power sources and DER as reactive power sources.

A. Conventional reactive power sources

Capacitors supply and reactors/inductors consume static reactive power and function in a discrete manner. These devices, if active, supply or consume a given amount of reactive power. Even though capacitors have some disadvantages, low speed of response and poor ability to support voltage stability, the investment and operating costs are low compared to dynamic sources (see table I).

Dynamic sources can be divided into generators, synchronous condensers, and flexible AC transmission systems (FACTS).

Generators produce real power as well as reactive power. A tradeoff exists between generator real and reactive power outputs, which are limited to the apparent power rating. Once the maximum apparent power is reached, supplying more reactive power requires the real power output be reduced Additionally, a generator's armature and field winding heating limits reactive power output. The associated costs for generator reactive power supply lie above those of static reactive power sources and will be discussed in detail in section III.

Synchronous condensers are synchronous generators that are redesigned to supply only reactive power. They have similar fast response times as generators, but are only useful at MVAr sizes.

FACTS can include dynamic VAr sources at the transmission level, which require high investment costs. [4,5,9]. Since dynamic sources are mainly used at higher voltages and do not compare well to the microgrid scale, only the static sources are included in the analysis with DER-CAM.

B. DER and reactive power

DER are able to supply reactive power depending on their grid-coupling converter. ICEs with synchronous generators can provide reactive power together with real power. Batteries, FCs, and renewable energy resources like PV typically produce DC, and use inverters to connect to AC grids, while MCs use DC internally. All these devices are sometimes capable of supplying reactive power depending on the capabilities of their power electronics [10].

Over-sizing the converter can provide a certain amount of reactive power output while operating at maximum real power rating. For example, over-sizing an inverter for 100 kW PV system by 5 percent leads to a secure supply of 32 kVAr at peak real power output. Over-sizing implies higher investment cost upfront, and typical levels are summarized in table 1 [9].

TABLE I
CONVENTIONAL AND DER REACTIVE POWER SOURCE CHARACTERISTICS

Reactive power source		Response speed	Voltage support	Investment cost ($/ kVAr)[3]
Capacitor/ reactors		Slow	Poor	10 - 30
Generators		Fast	Very good	-
Synchronous condenser		Fast	Very good	10 - 40
FACTS		Fast	Poor - Good	40 - 100
DER	Inverter	Fast	Good	40 - 90
	Synch. Generator	Fast	Good	25 - 40

III. REACTIVE POWER MARKETS

In order to assess the monetary incentives for power generators to participate in reactive power provision, a closer look at the market characteristics is necessary. Different compensation methods will be compared briefly and market examples will be given to determine the most reasonable approach for the microgrid's interaction with the macrogrid. This analysis sets the basis and constraints for the DER-CAM modeling described in section IV.

A. Reactive power market models

Historically, reactive power supply services are part of the vertically integrated industry in which generation, transmission and distribution were all provided by one centralized entity. Reactive power supply compensation would often be bundled with other ancillary services. Individual services would not be priced separately, which makes a detailed analysis of different tariffs difficult and does not facilitate a profound understanding of the value of reactive power supply. Our changing grid infrastructure and deregulation have put a spotlight on ancillary service responsibilities and forced grid operators and regulators to develop a new reactive power market framework. Four market frameworks are typically used:

1) No compensation:

Each real power generator is required to provide real

---

[3] Generators, DER inverters, and DER synchronous generators only require an additional over-sizing investment.

power with a certain power factor (PF) in order to connect to the grid.

2) Installed capacity/ capability:

With capacity compensation, the generator is paid in advance for its capability of producing or consuming a predetermined amount of reactive power quoted in kVAr. Sometimes the generator receives this payment as part of its real power capacity payment. There is no real-time pricing in this method, which means that there is no further payment for actual kVArh delivered within the predetermined range.

3) Cost-based compensation:

A cost-based approach can include the following cost components: additional investment cost, additional variable cost, and the opportunity cost of reactive power supply. Investment costs occur when generator over-sizing guarantees a certain reactive power supply at all times, or if the generator's purpose is only reactive power supply. Variable costs are incurred by any real power losses reactive output causes. Additionally, higher maintenance and reduced life expectancy are included in variable costs. Opportunity costs also occur if the generator is forced to produce reactive instead of profitable real power. The opportunity cost is valued at the foregone real power revenue estimated at the current electricity market price, or at the generator's incremental production cost. This approach can determine compensation per installed kVAr capacity. Alternatively, it can produce a payment for actual supplied kVArh of reactive power depending on the generator's specific reactive power production cost. In either case, fair compensation can be set.

4) Auction:

In an auction, a certain amount of kVArh capacity is needed. The system operator selects suppliers based on the market clearing price and local need for reactive power. Under this system, the operator predetermines its need for reactive power at different points in the system and provides the generators with voltage or reactive power schedules. Again, the generators have to derive their bid based on the costs described above [4-9].

Another viable option is a combination of capacity and real-time payments, which would have to be considered in the analysis.

B. *Different reactive power consumers*

Various actors need reactive power for different purposes. First, it is consumed by three different entities: loads, power generators, and network owners. Second, it is used to regulate voltage.

Electricity consumers' demand for reactive power is usually described by their PF. The system operator prefers a PF to be close to unity. In order to incentivize the load's participation in reactive power provision, the system operator requires a certain PF or penalizes a low one.[4]

In the grid, transmission lines act capacitively or inductively. Depending on the intensity of the current flow, lines can absorb or produce reactive power. High current flow during daytime leads to high reactive power consumption as well as a voltage drop, and vice-versa. In these conditions, the system operator becomes a reactive power consumer or producer. The operator has to compensate its real power generators for their consequent real power losses, with these costs passed on to ultimate customers through distribution and transmission charges.

Voltage control and reactive power management support the reliability of the network. Dynamic changes appear following a sudden generator loss, which leads to reduced reactive power supply and a reconfiguration of reactive power flows, which could cause the system to absorb more reactive power. Dynamic capacitive reactive power supply stabilizes or restores the voltage.

The system operator faces a trade off. On the one hand, it wants to consume as little reactive power as possible to save procurement cost. On the other hand, it has to guarantee reliable and efficient grid operation, which requires a costly reserve of reactive power sources. When the system operator has to force generators to produce reactive power to stabilize the system, another trade off becomes obvious: maintaining reliability vs. real power supply and energy balance [4].

A more recent voltage problem is observed in rural areas with high PV and wind penetration. High real power production and absent loads lead to increasing voltage in the distribution system. Inductive reactive power consumption is necessary to keep the voltage within limits and assure the system's ability to absorb generated real power [11]. Again, dynamic reactive power sources are more valuable to keep the system stable than static sources

The examples show the different incentives and tradeoffs the participants in reactive power markets face. An electricity consumer has to receive a signal from its system operator to correct its PF internally and not rely on external reactive power supply. The system operator has to determine where reactive power is needed within its area to provide reliable operations. In general generation and consumption of real power varies which does not make the pricing of the reactive power easier, since reliability can be seen as a public good. In the current system the costs are passed on to every end consumer independent of its location and reactive power consumption.

Reliability has a different value to each costumer, and providing reactive power has different costs to each potential supplier, and both issues have to be addressed by the tariffs. The stakeholders in reactive power markets should receive a clear price signal to participate actively in the market.

C. *Examples for reactive power compensation*

Compensation for reactive power varies across jurisdictions. This section outlines some examples in the US and internationally.

The New York Independent System Operator (NYISO) uses the capability compensation approach plus lost opportunity cost compensation. All generators and

---

[4] A PF at one would lead to the danger of self excitement for asynchrony machines, as well as, excess voltage with isolation of lines and end consumer devices.

qualified non-generator resources are paid \$3.92/kVAr per year for the voltage support service. Additionally, a generator receives an opportunity cost payment when the ISO forces the supplier to lower its real power output below its economic operating point [12].[5]

The California Independent Service Operator (CAISO) requires generators to operate within a PF range of 0.90 lagging and 0.95 leading. It pays generators their opportunity cost when it forces them to dispatch reactive power outside this range [13].[6]

In the United Kingdom the price for reactive power support is determined through an auction. Generators include in their bids for voltage support a capacity component (£/VAr) and a utilization component (£/VArh). Afterwards, the chosen generators enter an annual contract with the system operator independently. In March 2011 utilization compensation was at \$0.0045/kVArh[7] [14].

The Pacific Gas and Electric Company (PG&E), the northern Californian distribution utility, prefers its customers with a peak demand above 500 kW to maintain a PF of ≥0.85. The customer gets penalized if its PF falls below this value and receives payments for a PF higher than 0.85. The payment is determined by the following equation [15]:

$$\begin{aligned}&Payment =\\ &Power\ factor\ adjustment\ rate\ \left(0.00005\ \frac{\$}{kWh{\cdot}\%}\right)\cdot\\ &Power\ factor\ adjustment\ \left(Difference\ to\ 0.85\ (\%)\right)\cdot\\ &Real\ power\ consumption\ (kWh) \qquad (2)\end{aligned}$$

With this method the real power consumption has a direct impact on the reactive power payment.

D. Reactive power markets for microgrids

The FERC study points out that a well-designed pricing mechanism is the key to an efficient reliable reactive power market. The mechanism must establish a clear price signal that encourages generators close to loads to participate in the reactive power market [4].

Microgrids appear to be good candidates for meeting these requirements, being able to optimize reactive power demand locally and provide voltage support to the local network. Especially, the possibility of dynamic voltage support through synchronous machines or inverters could add a significant local benefit. Local reactive power control enables higher real power transport and reduces losses. The next section analyzes possible benefits and determines the compensation method that provides the right price signal to microgrids for participation in reactive power markets.

Matching different described compensation approaches with a microgrid's advantages, the following price signals will be analyzed: (1) capacity compensation (\$/kVAr), (2) utilization compensation (\$/kVArh), (3) the PG&E PF incentive approach, (4) percentage reduction in the distribution charge of the tariff. Every customer usually pays a fixed price per kWh, which includes generator and distribution charges. The distribution charge is basically a compensation for building and operating the distribution network, including necessary ancillary services. This follows the logic that local voltage support and internal reactive power optimization would lead towards less reactive power supply by the system operator, as well as lower real power losses. The system operator decreases its own reactive power costs and is able to pass on this benefit to its customers.

IV. DER-CAM AND REACTIVE POWER

Originally, DER-CAM was developed as a tool for finding the combination of DER with minimum energy cost and/or CO_2 emissions as well as the equivalent optimal operation schedule [16,17]. The optimization problem is formulated as a mixed integer linear program, written in the General Algebraic Modeling System (GAMS®). DER-CAM choose among a set of distributed generators, electricity purchases and natural gas to meet energy services demand considering market information such as the regulatory framework as well as technical constraints.

Over the years, DER-CAM has been extended and currently two versions exist [18]:

1) *Investment & Planning DER-CAM* finds the optimal investment decision based on historically observed load profiles and considers the operation of the selected equipment for a test year.

2) *Operations DER-CAM* uses the optimal DG equipment delivered from the Investment & Planning DER-CAM or site specific installed equipment to perform load predictions for the next seven days and optimizes the operational schedule of the pre-defined DER equipment for an energy cost and/or CO_2 emissions minimum solution.

In current research both DER-CAM versions have been extended by addition of a reactive power option. Only the Investment & Planning version will be described in the following subsection.

A. Implementing a reactive power model with DER-CAM

While the existing DER-CAM versions minimize energy costs and/or CO_2 emissions, we have implemented two approaches to model the microgrid's reactive power supply:

1) Minimum cost: A minimum cost reactive power supply for a given demand

2) Maximum microgrid profit: This approach adds the option of procuring reactive power from the grid. Variations of the grid price, as well as, possible kVArh sales allow a sensitivity analysis.

The minimum cost approach will provide an upper boundary for the cost impact and can be compared to the above described four compensation alternatives: 1) kVAr payment, 2) kVArh payment, 3) PG&E approach, 4)

---

[5] This payment is calculated based on the following components: the output reduction in real power, the time duration of reduction, and the real-time marginal price at the generator bus minus the generator's energy bid for the reduced output of the generator.

[6] For details on the lost opportunity cost calculation see CAISO tariff section 8.2.3.3.

[7] Price in March 2011: £0.0028/VArh. Converted with an exchange rate of 1.61 \$/£

reduction of the distribution charge for real power.

The demand for reactive power serves as already described two different purposes: 1) the microgrid's electric loads consume reactive power – internal demand; 2) the system operator needs reactive power for voltage support – external demand. Here internal demand is modeled as a fixed PF, for example 0.85. The reactive power necessary to bring the PF close to unity describes reactive power demand that has to be met by the microgrid's reactive power production. The voltage support for the grid is modeled as a continuous reactive power dispatch. Another possibility is to model this external demand according to a voltage support schedule provided by the grid operator.

In DER-CAM the reactive power demand must be met at all times and is therefore a hard constraint. In order to fulfill this, the solver has the option to choose between the microgrid's DER, capacitors and reactors, as well as, procuring reactive power from the grid in the second approach. Since the optimization is set to provide a cost minimum solution, DER-CAM considers the following costs: investment and variable costs of reactive power supply. The lost opportunity costs are neglected in this approach due to the following reasons:

The value of real power is in general much higher than the value of reactive power. The examples indicate a ratio of 20-to-1 or even higher. Additionally, the lost opportunity costs appear only in case of a reduction of the real power output, which is not the case in our DER-CAM examples.

The non-linear relationship between reactive power and real power demands a two-step modeling approach to real and reactive power supply since DER-CAM is set up as linear optimization. First, DER-CAM optimizes the real power. This includes the investment decision in DER and the associated operation schedule. Afterwards, the reactive power supply is optimized according to minimum over-sizing investment and minimum operating costs.

B. *Modeling the cost of reactive power supply*

DER-CAM finds the minimum costs for reactive power supply by considering the additional investment and variable costs of reactive power supply. In this approach the variable costs are determined through the additional losses of real power the converter produces when supplying reactive power [10]. These losses depend on the converter's efficiency, its underlying source, the installed capacity and the real power output. These four inputs are necessary for the optimization. An overview over representative DER, their converter type, and their converter efficiencies is listed in table II.

TABLE II
EXAMPLE OF POWER RESOURCES IN DER-CAM

DER	Size	Converter	Converter efficiency
Internal Combustion Engine (ICE - small)	60 kW	SG	97 %
Microturbine (MT - small)	60 kW	Inverter	95 %
Fuel Cell (FC - small)	100 kW	Inverter	95 %
PV	variable	Inverter	96 %

Knowing the converter's efficiency curve η, the additional losses P_{Losses} can be determined as function of the maximum apparent power S [20]:

$$P_{Losses}(S) = \frac{1-\eta(S)}{\eta(S)} \cdot S \qquad (3),$$

This allows the approximation of a P_{Losses}-curve and to determine the constants in eq. 4:

$$P_{Losses}(S) = c_{self} + c_{volt} \cdot S + c_{cur} \cdot S^2 \qquad (4),$$

where c_{self} describes the internal losses, c_{volt} the losses dependent on voltage, and c_{cur} the current determined losses.

Using equation (1) in (3) and (4) provides the additional real power losses for every reactive-real power point combination [20]:

$$P_{Losses}\left(\sqrt{P^2+Q^2}\right) = c_{self} + c_{volt} \cdot \sqrt{P^2+Q^2} + c_{cur} \cdot (P^2+Q^2) \qquad (5)$$

Scaling these losses to the maximum apparent power allows a reactive power loss graph to be plotted (see. Fig. 1). DER-CAM uses these additional loss-curves to determine the cost minimum solution for the additional losses.

The real power optimization (step1 described above) determines two of the four necessary input parameters for the reactive power model: the installed DER capacity and the real power output. The converter type and its efficiency are fixed. The solver is now able to determine the sources that provide the lowest cost for additional losses. The costs of the additional losses depend on the energy value of the underlying DER. If the DER has not yet reached its maximum real power output, the value of the additional losses equals the generation cost for these losses, i.e. fuel consumption. If real power output is at its maximum, the value of the additional losses is equal to the value of the electricity purchased from the utility. A PV system, for example, is assumed to always put out maximum real power given incident solar radiation, hence the cost of additional losses from reactive power can be valued at the current market price.

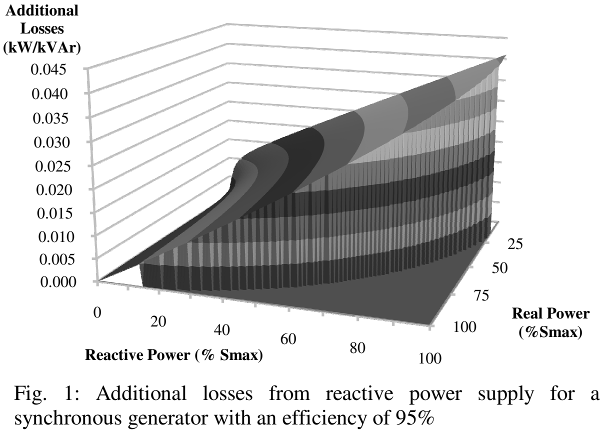

Fig. 1: Additional losses from reactive power supply for a synchronous generator with an efficiency of 95%

The investment decision of the reactive power model provides DER-CAM with the option to over-size the converters or invest in capacitors and/or reactors. The solver chooses between over-sizing the converter by 5% - 30%[8] of its original rating determined by the investment DER-CAM. The additional investment costs per kVAr are listed in table I. Additionally, the installation costs, as well as maintenance cost and the lifetime of the converter, are included in the analysis. Based on these inputs DER-CAM compares the annuities of alternative investments.

V. CASE STUDY

This example analysis concerns a large hospital in San Francisco with electricity load profiles based on a California Commercial End-Use Survey building [19]. The building has a peak electricity demand of 1,894 kW, and a total annual consumption of 11.07GWh. Fig. 2 shows typical *weekday* profiles for representative summer and winter months. For each month, two other day types were created, *weekends*, and *peak days*. The monthly *peak days* are calculated as the average of the three weekdays with highest consumption.

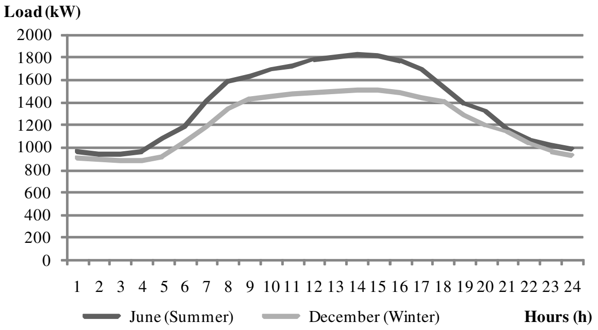

Fig. 2: Representative *weekday* real power profiles

A small difference between summer and winter can be observed, with higher electricity demand in summer. Over the course of average days, regardless of the month or season, consumption increases sharply in the morning hours and reaches a smooth maximum during the early afternoon, before decreasing in the afternoon.

TABLE III
PG&E TARIFF FOR CUSTOMERS OVER 500 KW – E-19 TARIFF

	Summer (May – Oct.)		**Winter (Nov. – Apr.)**	
Electricity	**electricity ($/kWh)**	**demand ($/kW/mon.)**	**electricity ($/kWh)**	**demand ($/kW/mon.)**
on-peak	0.16	13.51	-	-
mid-peak	0.11	3.07	0.09	1.04
off-peak	0.08	-	0.08	-
customer chg. ($/month)	406.57			

Table III shows the PG&E tariff applied to the health care building [15]. Winter (Nov-Apr) rate periods are: mid-peak (08:00-21:00) and off-peak (all other times). In summer (May-Oct.), a third on-peak period (12:00-18:00) is added. The demand charge is per maximum kW monthly load, irrespective of the time of occurrence.

The reactive power demand is simulated for a constant PF of 0.80 – 0.95 in 5%-steps. Additionally, a continuous voltage dispatch of 5% of the microgrid's reactive power demand is simulated. Fig. 3 shows the reactive power demand for a constant PF of 0.85 for the two months.

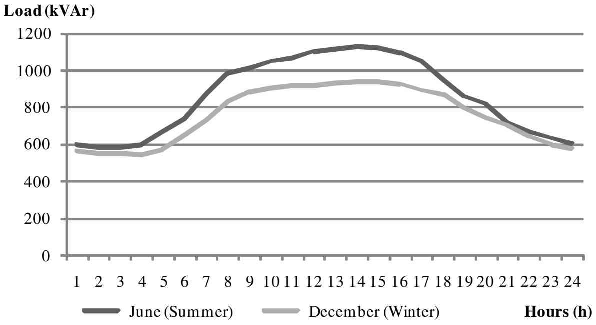

Fig. 3: Representative *weekday* reactive power profiles

The Investment DER-CAM optimization leads to a real power cost minimum installation of five medium-sized internal combustion engines. Since this solution does not allow a closer study of the effects of the different possible DER supplying reactive power, a scenario analysis is performed with a fixed number of DER. The two scenarios are displayed in table IV.

TABLE IV
INSTALLED DER FOR CASE STUDY

DER	Scenario 1	Scenario 2
ICE - small	60 kW	180 kW
ICE - medium	250 kW	500 kW
Microturbine - small	60 kW	180 kW
Microturbine - medium	150 kW	300 kW
Fuel Cell - small	100 kW	200 kW
Fuel Cell - medium	250 kW	500 kW
PV	100 kW	100 kW

VI. RESULTS

The analysis points out two different aspects. First, the scenarios are compared to analyze what DER technologies are used to supply reactive power and how much is invested in conventional sources compared to DER. Additionally, the impact of procuring reactive power from the grid is analyzed. Then, the different compensation approaches are compared.

Fig. 4 shows how the reactive power demand, described in section IV, is met by the microgrid's sources. The split between conventional and DER reactive power sources is about half. The DER the ICE-medium and the MT-small provide the highest amount of reactive power. The trade-off between variable and investment cost becomes visible. Real power is mainly supplied by the ICEs and additional reactive power losses decrease according to fig. 1. Over-sizing them by more than 5% would be more expensive than using the equipment already installed, which produces higher additional losses per kVArh generation. Other import

---

[8] In 5% steps

factors are the converter's efficiency, which influences the kWh-losses per kVArh, as well as, the source's kWh-value. As stated, depending on the source's real power generation the additional losses are either valued at the costs for additional natural gas fuel used to generate a kWh, or at the applying tariff for buying real power from the grid if the source is at maximum real power output. Especially, during the peak hours of the day, when grid purchases are expensive, one can see that the solver chooses reactive power from sources that are not at maximum real power output because of the costs. Another interesting observation is that the PV system is barely used to supply reactive power since additional losses are also valued at the electricity tariff compared to DG where natural gas consumption determines the value of the losses.

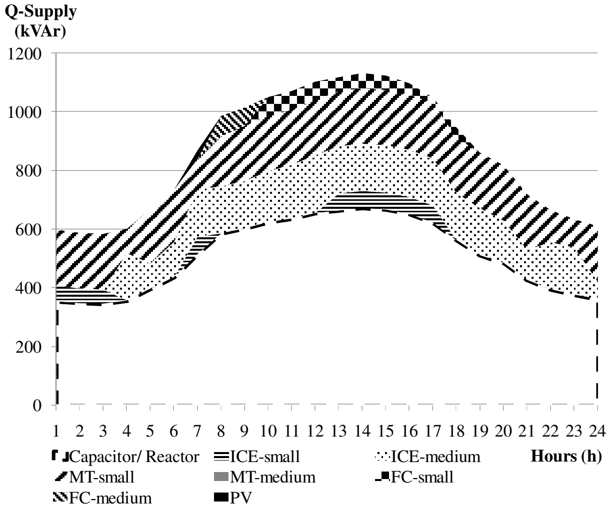

Fig. 4: Reactive power supply for scenario 2 for the month of June

In comparison to scenario 1, the main difference in 2 is the amount of installed static sources. DER-CAM chooses static sources with the lower investment cost rather than over-sizing DER converters at larger scale.

Sensitivity analyses are performed to determine how the possibility of procuring reactive power from the grid changes the microgrid costs, benefits, and PF. Procurement costs are varied from $0 - $0.004 /kVArh, compared to receiving a benefit for supplying reactive power, varying from $0.0005 - $0.0025 /kVArh.[9]

The following conclusions can be drawn from this analysis: Depending on the demand, the break-even-point lies between a compensation of $0.0013 - $0.0015 /kVArh for scenario 1 and between $0.0010 - $0.0013 /kVArh for scenario 2. Once the microgrid receives such compensation, the benefits outweigh even lower grid procurement costs. The higher the difference between benefits received and procurement costs, the more is invested in local reactive power generation.

Fig. 5 displays an example of how the grid purchasing option changes reactive power supply. In this case it is assumed that the microgrid buys reactive power for $0.0005 /kVArh, but would receive $0.0015 /kVArh for voltage support. Compared to the other case the microgrid's profit actually increases by approx. $180 per year. Even though its revenue from reactive power sales is lower, this it outweighed by the cost savings.

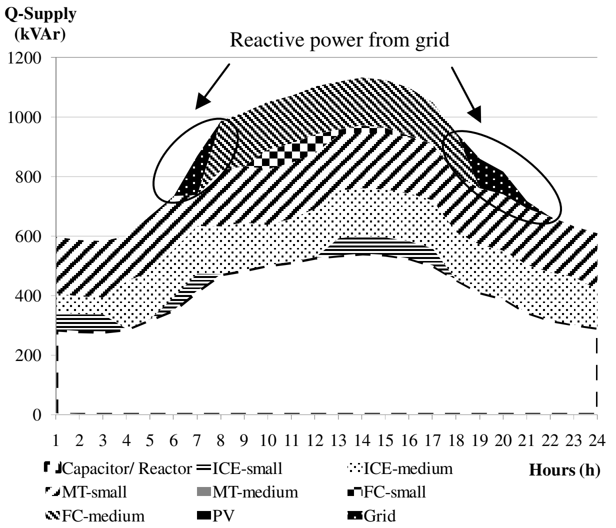

Fig. 5: Reactive power supply for scenario 2 with enabled grid procurement for the month of June

The microgrid purchases reactive power in hours, where the tariff switches from off-peak to mid-peak and from on-peak to mid-peak. DER real power generation during peak hours is economical. A high real power output allows a minimally over-sized converter to produce reactive power at low incremental losses. DER real power generation decreases at off-peak times, and their reactive power supply becomes more expensive. Since DER-CAM now has the option of purchasing from the grid during those times, it can decrease its overall capacitor investment. During the peak times, capacitors are substituted by over-sized DER.

Table V summarizes the necessary compensation value to generate a profit for the microgrid and incentivize its participation in reactive power markets.

TABLE V
BREAK-EVEN-POINT FOR DIFFERENT COMPENSATION METHODS

Compensation method	Scenario 1	Scenario 2
Capacity (kVAr)	$7.7 - 8.5 /kVAr	$6.1 - 7.7 /kVAr
Utilization (kVArh)	$0.0013 - 0.0015/kVArh	$0.0010 - 0.0013/kVArh
PG&E approach	Not profitable	Not profitable
% of tariff	6% - 15%	12% - 36%

Compared to the compensation examples, the capacity payment lies about $2-4 /kVAr above the payment of the NYISO. The utilization rate lies about $ 0.003/kVArh below the British one. The PG&E approach leads to loses for the microgrid, since the payment is connected to consuming real power from the utility, while the microgrid self-generates a significant share of its requirement onsite. The conclusion is similar for the reduction of the distribution charge. The more electricity is generated onsite the less is consumed from the grid and the higher the percentage value get needed to break even for the onsite reactive power supply.

---

[9] Procurement cost as well as reactive power benefit are analyzed in $0.0005 /kVArh-steps.

VII. CONCLUSIONS

Microgrids have the technical ability to participate in reactive power markets. With dynamic DER they can provide valuable voltage support. The analysis shows that a well weighted mixture of comparably more expensive dynamic DER and less costly static reactive power sources could provide the necessary reserve to support grid performance.

Economically the capacity compensation or the utilization compensation sends the right price signal to encourage microgrids to play an active role in reactive power markets. The calculated compensation ranges seem to be competitive compared to conventional reactive power sources. Additionally, dynamic characteristics of supply would justify a small mark up.

This paper analyzes compensation ranges from a microgrid cost perspective for only one case study. To validate the results additional case studies are necessary. Further research should investigate the system wide impacts of microgrid participation in reactive power provision and calculate the monetary benefits for the system operator.

ACKNOWLEDGMENT

The authors acknowledge the contributions of prior members of the DER-CAM development team. In addition, the authors are grateful for valuable input by Prof. Thomas Hartkopf from TU Darmstadt.

REFERENCES

[1] Y. Rebours, D. Kirschen, M. Trotignon, and S. Rossignol, “A Survey of Frequency and Voltage Control Ancillary Services - Part I: Technical Features,” *IEEE Transactions on Power Systems,* vol. 22, no. 1, pp. 350-357, February 2007.

[2] International Electrotechnical Commission, “IEV number617-03-09”, Electropedia Vocabulary – Area: Organization/ Market of electricity / Market organization and technical constraints, March 2009.

[3] F. Saccomanno, *Electric power systems – Analysis and Control,* Wiley, New York, 2004.

[4] Federal Energy Regulatory Commission, “Principles for Efficient and Reliable Reactive Power Supply and Consumption,” Staff Report, Docket No. AD05-1-000, February 2005.

[5] Oak Ridge National Laboratory, “A Preliminary Analysis of the Economics of Using Distributed Energy as a Source of Reactive Power Supply,” ORNL/DOE Report, April 2006.

[6] Microgrid Exchange Group, October 2010.

[7] Microgrid Symposiums, Berkeley (USA), 2005, Montréal (Canada) 2006, Nagoya (Japan), 2007, Kythnos (Greece), 2008, San Diego (USA),2009, Vancouver, (Canada), 2010.

[8] C. Tufon, A. Isemonger, B. Kirby, J. Kueck, F. Li, “A Tariff for Reactive Power,” IEEE PES Power Systems Conf. and Expo. (PSCE 2009), Seattle (USA), March 2009.

[9] J. Kueck, B. Kirby, T. Rizy, F. Li, N. Fall, “Reactive Power from Distributed Energy”, The Electricity Journal, vol. 19, no. 19, pp. 27 - 38 , December 2006.

[10] M. Braun, *Provision of Ancillary Services by Distributed Generators – Technological and Economic Perspective,* kassel university press, Kassel, Germany, 2008.

[11] M. Braun, T. Stetz, T. Reimann, B. Valov, G. Arnold, “Optimal reactive power supply in distribution networks - technological and economic assessment for PV-system,” European Photovoltaic Solar Energy Conference (EU PVSEC 2009), Hamburg (Germany), September 2009.

[12] New York Independent System Operators, Inc., “NYISO Tariffs – MST Section 15, Rate Schedules,” March 2011.

[13] California Independent System Operator, “Conformed Fifth Replacement CAISO Tariff as of February 1, 2011,” February 2001.

[14] National Grid Company, “Obligatory Reactive Power Service (ORPS): Default Payment Rate,” March 2011

[15] Pacific Gas and Electric Company, “Electric Schedule E-19”, May 2010.

[16] A. Siddiqui, R. Firestone, S. Ghosh, M. Stadler, C. Marnay, and J. Edwards, “Distributed Energy Resources Customer Adoption Modeling with Combined Heat and Power Applications,” Lawrence Berkeley National Laboratory Report LBNL 52718, 2003.

[17] C. Marnay, G. Venkataramanan, M. Stadler, et al., “Optimal Technology Selection and Operation of Commercial Building Microgrids,” IEEE Transactions on Power Systems, vol. 23(3), August 2008.

[18] M. Stadler, J. Donadee, C. Marnay, G. Mendes, J. von Appen et al., “Application of the Software as s Service Model to the Control Complex Building Systems,” ECEEE 2011 Summer Study, Toulon (France), June 2011.

[19] Itron, Inc., “California Commercial End Use Survey,” prepared for the California Energy Commission, CEC-400-2006-005, 2006.

[20] M. Braun, “Reactive Power supplied by PV Inverters – Cost-Benefit-Analysis,” 22nd European Photovoltaic Solar Energy Conference (EU PVSEC 2007), Milan (Italy), September 2007.