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Terance J. Harper
*Purdue University, United States of America*, harper18@purdue.edu

William J. Hutzel
*Purdue University, United States of America*, hutzelw@purdue.edu

Athula Kulatunga
*Purdue University, United States of America*, nkulatun@purdue.edu

J. Christopher Foreman
*Purdue University, United States of America*, foremanj@purdue.edu

Aaron L. Adams
*Alabama A&M University, United States of America*, aaron.adams@aamu.edu

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# Microgrids for Improving Manufacturing Energy Efficiency

Terance HARPER[1]*, William J. HUTZEL[1], N. Athula KULATUNGA[1], J. Christopher FOREMAN[1],
Aaron L. ADAMS[2]

[1]Purdue University, Department of Engineering Technology,
West Lafayette, Indiana, USA
Harper18@purdue.edu, Hutzelw@purdue.edu, Nkulatun@purdue.edu, Foremanj@purdue.edu

[2]Alabama A&M University, Department of Engineering, Construction Management and Industrial Technology,
Huntsville, Alabama, USA
Aaron.adams@aamu.edu

* Corresponding Author

## ABSTRACT

Thirty-one percent of annual energy consumption in the United States occurs within the industrial sector, where manufacturing processes account for the largest amount of energy consumption and carbon emissions. For this reason, energy efficiency in manufacturing facilities is increasingly important for reducing operating costs and improving profits. Using microgrids to generate local sustainable power should reduce energy consumption from the main utility grid along with energy costs and carbon emissions. Also, microgrids have the potential to serve as reliable energy generators in international locations where the utility grid is often unstable. For this research, a smart microgrid system was designed as part of an innovative load management option to improve energy utilization through active Demand-Side Management (DSM). An innovative Demand-Side Management (DSM) strategy was developed as part of a smart microgrid system to improve the energy utilization for a manufacturing process. The DSM algorithm managed the intermittent nature of the microgrid and the instantaneous demand of the manufacturing process. The control algorithm required two input signals; one from the microgrid indicating the availability of renewable energy and another from the manufacturing process indicating energy use as a percent of peak production. Based on these inputs the algorithm had three modes of operation: normal (business as usual), curtailment (shutting off non-critical loads), and energy storage. The results show that real-time management of a manufacturing microgrid has the potential for saving energy and money by intelligent scheduling of process loads.

## 1. INTRODUCTION

The Applied Energy Laboratory (AEL) and a consortium of manufacturer's through Purdue University's Center for Technology Development (CTD) are investigating microgrids for manufacturing facilities to improve energy utilization through intelligent load management. A prototype microgrid system consisting of solar panels and manufacturing process loads was designed and built to test these concepts. The goal for this ongoing research is to demonstrate potential for reducing electrical consumption and peak demand from the utility grid while maintaining high levels of manufacturing productivity.

The manufacturing process is the core of many manufacturing enterprises (Zhou, 2011), in which operations such as machining, inspection, transportation, and assembly consume large amounts of energy. For this reason, energy efficiency in manufacturing facilities is increasingly important for reducing operating costs and improving profits. According to Zhou (2011), the energy consumption level in manufacturing is higher than that of other commercial enterprises, and the potential for energy savings is large.

With the rise in electrical energy costs, an awareness of high-energy consumption at manufacturing facilities is important to offset time-of-day and tariff rates. Peak demand surcharges billed by utility companies are a significant part of a typical manufacturer's total electric bill. To investigate and correct peak demand, DSM was developed and practiced by industries to become more energy efficient (York, Kushler, & Witte, 2007). York *et al.* (2007) states that the very premise of DSM is that there are benefits to both utilities and their customers to change energy use patterns, whether by shifting demand to different periods, reducing demand at specific times, or reducing overall energy use through energy-efficient technologies. This is where integrating microgrids to the energy plan of a manufacturing plant has potential, due to utility system peak loads coinciding with long, hot sunny days during the summer when high solar insolation is also available for a solar photovoltaic (PV) energy system associated with a microgrid (Byrne, Hegedus, & Wang, 1994).

Recently, governmental agencies and congress have begun focusing global economic and industry policies on renewable energies (Schleicher-Tappeser, 2012). With growing awareness of cleaner alternatives to fossil fueled power generation plants, renewable energy systems are becoming more attractive and sustainable for the future of companies. According to Singh & Alapatt, 2012, both grid-tied and stand-alone PV energy systems have the distinct advantages of economic predictability, low maintenance and downtime expenses, zero refueling costs, and fast construction time. In all, offsetting energy consumption with "green power" clearly has advantages for manufacturers, not only in terms of reduced operating costs, but also in terms of the positive corporate image resulting from actively engaging in sustainable business practices (Lunt & Levers, 2011).

Microgrids have attracted much attention to provide a reliable, efficient, economic, and sustainable energy supply in alternative energy initiatives all around the world (Bozchalui & Sharma, 2012). As shown in Figure 1, microgrids include, but are not limited to, a supply side, distributed storage, and a demand side. Though microgrids have islanding capabilities, most microgrids are interconnected to the main utility as well. The supply side is a variety of renewable energies and conventional combined heat and power units used to generate locally accessible electricity. In addition to the supply side is energy storage through the use of batteries, flywheels, fuel cells, or electric vehicles. The demand side is all energy-consuming processes that include critical, curtailable, and schedulable loads.

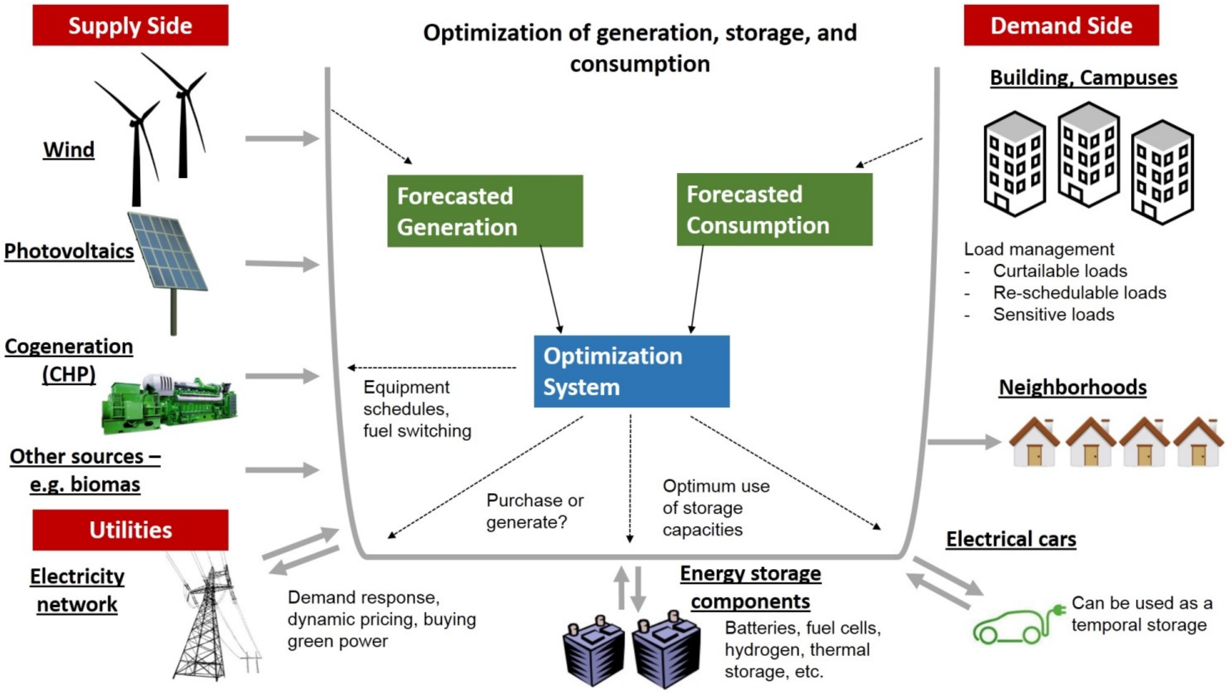

**Figure 1.** Schematic Representation of a Microgrid, (Stluka, Godbole, & Samad, 2011)

Although the hardware for microgrids is well understood, there are significant opportunities for "optimization" that is shown at the center of Figure 1. There is a lack of decision support when procuring, distributing, and accounting for energy in production systems, which leads to high-energy cost with low energy efficiencies Stluka *et al.* (2011). In order to achieve desired optimization Stluka *et el.* (2011) proposed optimizing the supply-side, integrating renewable energies, optimizing energy storage, optimizing demand-side, forecasting loads, and forecasting renewable generation. This research developed a comprehensive strategy that accounted for both supply side and demand side in order to save energy and money.

## 2. TEST PLATFORM

This research project built the first grid-interactive renewable energy installation on the academic campus of Purdue University in West Lafayette. This was a significant accomplishment in and of itself because the institution is cautious about anything that has the potential for disrupting research and other mission critical activities. This first project will make renewable energy installations on campus easier to accomplish in the future.

### 2.1 Microgrid Prototype

For the last 10 years, the AEL has maintained a 3 kW solar PV array mounted at 45° with respect to latitude and at an azimuth angle of 180° as shown in Figure 2a. The array consists of 24 Kyocera 120-watt solar panels that were originally designed to be grid independent; meaning that the electricity was stored in batteries. The solar power was used for running several local pumps and fans in the laboratory, but did not have access to the electric grid. To fully enable the microgrid research, several electrical infrastructure upgrades were needed. The specific tasks included electric work to grid-tie the existing solar PV array to Purdue University's electrical infrastructure. An interactive three-phase grid-tie inverter was installed, in place of an old single-phase inverter, to mimic industrial facilities receiving AC power from three circuit conductors at 480 or 120/208 volts, as shown in Figure 2b. Unlike traditional microgrid solutions, the microgrid for this study did not include islanding capabilities.

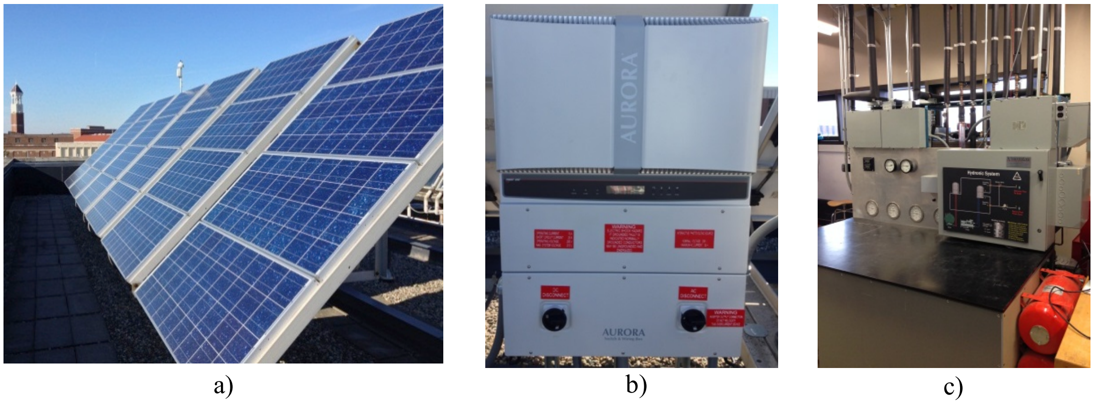
a) b) c)

**Figure 2.** Prototype Microgrid and Process Loads

### 2.2 Manufacturing Process

Figure 2c shows a process heating and cooling system used to simulate demand-side loads for this research. The system was intelligently controlled through a building automation platform. The system has four pumps (A, B, C, and D), one electric heating unit, and an external air-cooled chiller. Each pump is rated at 250W for a total of 1kW of electric demand. The electric heating unit has a steady demand of 9kW when heating was enabled. The chiller has a range of 500W-4,000W of electric demand when enabled. For the DSM research, Pump B, C, and D were chosen as the loads that would be curtailed when curtailment schemes were enabled. To simulate an energy storage scheme, either the process heating or cooling could be operated for thermal storage mode using 40 gallon tanks.

### 2.3 Supervisory Control and Data Acquisition (SCADA)

As shown in Figure 1, microgrids have very different types of equipment to monitor and control. To perform optimally, the supply side and demand side must have a common communication platform or at least some way of collecting and sharing data. The ability to coordinate data from multiple sources into one platform was essential to this research.

On the supply side, the three phase interactive inverter used for this research read and wrote real-time data to the manufacturer's proprietary data acquisition platform. The real time information included measurements of power and energy for each sub-array. The data acquisition platform was also connected to an external weather station so that temperature, humidity, and solar intensity were tracked in real time. All of this information was transmitted via Ethernet using Modbus TCP/IP so that data could be viewed on the inverter manufacturer's website or transferred to a third-party SCADA platform over a network. The common communication protocol is what enabled the communication between the supply side to the demand side of the microgrid.

On the demand side, the simulated manufacturing process was monitored and controlled using a building automation platform called WebCTRL from Automated Logic Corporation. Algorithms were developed in WebCTRL that monitored and controlled the process loads. This building automation platform allowed scheduling of the process loads to mimic a single shift of production at a manufacturing enterprise. This system also had sensors that monitored electrical energy use of the pumps, heater, and chiller used for process loads.

WebCTRL was also the SCADA system that linked the supply side and demand side of the microgrid. Using its network Modbus interface, WebCTRL collected real-time data on renewable energy production and weather conditions. With the supply side and demand side information on the same SCADA platform, developing process control strategies became relatively easy. The web-based platform also made it easy to manage this process from remote locations without direct access to the process loads in the laboratory or the solar panels on the roof.

## 3. METHODS

The objective was to develop and evaluate a prototype microgrid platform and optimal DSM control strategies to reduce electrical consumption and peak demand in a laboratory environment.

### 3.1 Demand-Side Management Model

Figure 3 shows a diagram of the DSM model that was developed to manage the intermittent nature of the microgrid and process loads and to determine optimal control outputs. The model used an algorithm that required an input from the microgrid, an input of energy demand from manufacturing processes, and historical data to actively determine optimal control strategies.

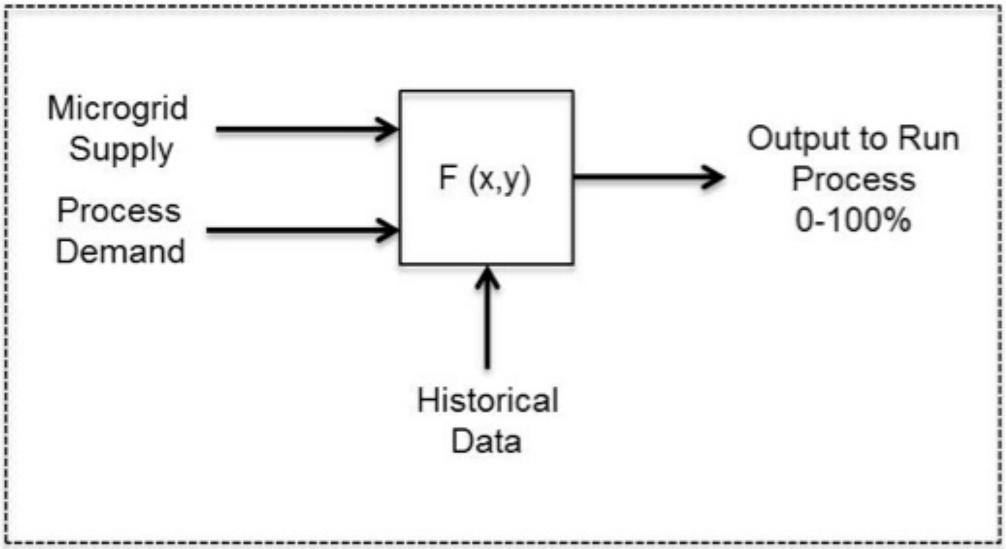

**Figure 3.** Demand-Side Management Model

The microgrid supply is a variety of distributed generation and storage technologies used to provide locally accessible electricity. These technologies include, but are not limited to, solar, wind, cogeneration (CHP), battery storage, and fuel cells configured in complex or stand-alone setups. Depending on technologies that are used to represent a functional microgrid, the sum of instantaneous power generation (kWh) will be used as the microgrid supply input.

Process demand is the total electricity from all energy consuming processes. This includes critical processes, curtailable processes, and re-schedulable processes, as determined by facility engineers. Critical processes are loads that cannot be interrupted and need a steady, reliable supply of electrical energy. Curtailable processes are loads that can be cycled, switched, or shut down to maintain processes but reduce energy consumption. Re-schedulable processes are loads that can be rescheduled for use during off-peak hours when electrical costs are cheaper.

Two types of historical data are needed. One is the past generation data for all renewable energy technologies. Historical renewable energy data is obtained from databases managed by the National Renewable Energy Laboratory (NREL). NREL maintains the web-based software tool called PVWatts that provided historical hourly and monthly solar irradiance levels.

The other historical data is the energy usage at a given facility, which is obtained by metering the overall consumption of the facility on a daily, weekly, or monthly basis. Based on how the facility is metered, the historical demand can be scaled hourly to correlate with the work shifts for a given facility to output process demand.

The output signal to the controllable process was determined by an algorithm that analyzed ratios from the microgrid supply and process demand. The ratio of microgrid power generation to historical generation is computed and converted to an equivalent percentage that provides parameters for the DSM algorithm to determine an optimal control strategy. Similar to the microgrid supply, the ratio for process demand is hourly process usage to hourly historical usage and is converted to an equivalent percentage. Depending on the ratios, the algorithm made decisions once an hour to optimally control processes.

## 3.2 Demand-Side Management Control Program

Figure 4 is the DSM algorithm that was developed to prioritize five optimal control strategies. The control modes were operated between 9:00a.m. and 5:00p.m. to replicate a single shift in manufacturing. The process heating and cooling system served as the simulated manufacturing process since pumps are typical loads found in manufacturing facilities. The five control programs that were investigated the DSM model were; all pumps run on continuous cycle with storage (Normal Operations with Storage), all pumps run on continuous cycle (Normal Operations), two pumps run continuous and two pumps run 20-10 on-off cycle (Pumps C and D), one pump run continuous and three pumps run 15-15 on-off cycle (Pumps B, C, and D), and no microgrid (Normal Operations). These control modes will depend on the relations of microgrid ratio and demand ratio.

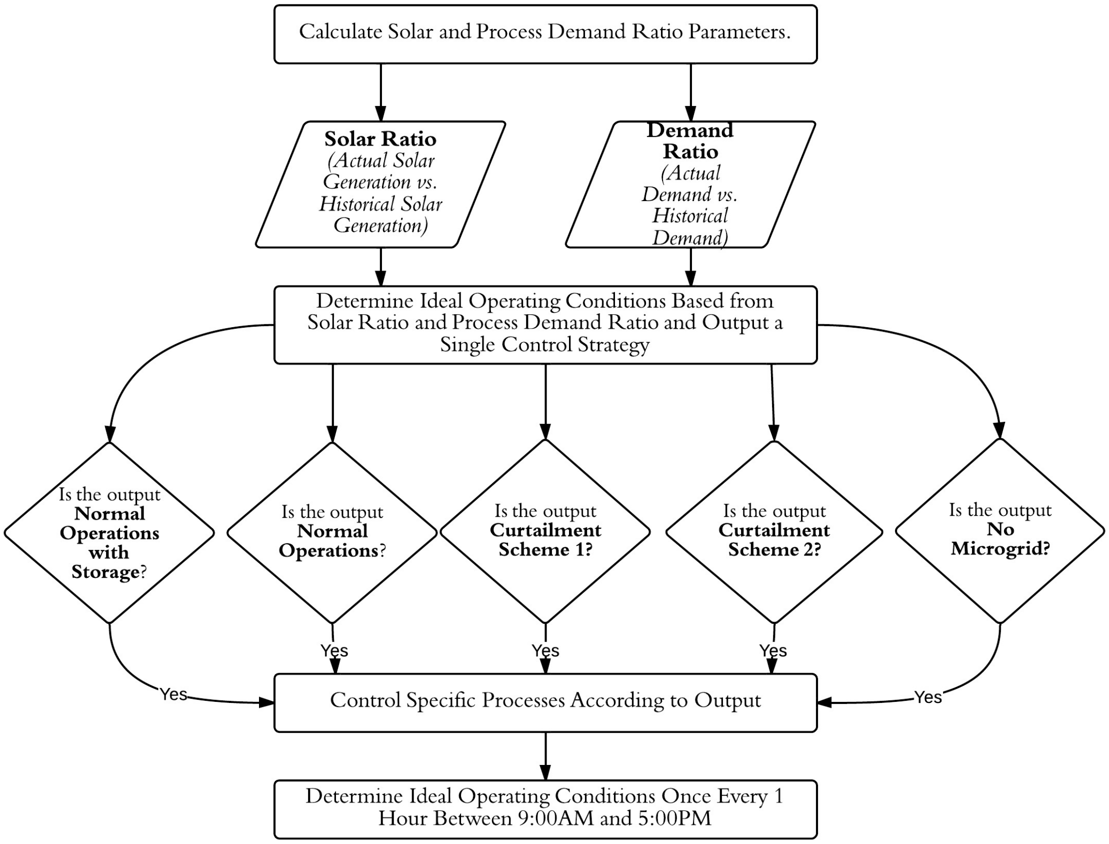

**Figure 4.** Demand-Side Management Flowchart

# 4. RESULTS

Data was measured and recorded using WebCTRL. Load status, load energy consumption, microgrid instantaneous power, and microgrid instantaneous generation were used to evaluate the DSM program and the impact toward reducing energy consumption. A default start at 9:00a.m. was enabled to allow the DSM program to calculate the demand ratio for the first hour of operation. This default start assisted with optimally controlling the simulated processes throughout the day. The DSM program was evaluated based on three microgrid generation supplies: excellent supply generation, good supply generation, and poor supply generation.

Figure 5 summarizes the DSM algorithm in operation for one day. This trend is taken from WebCTRL and there are three sections to the figure. The first section is the on/off status of Pumps A, B, C, and D. Within this section the end-user can see whether the pumps are in normal operation or curtailments throughout the day. The second section is the instantaneous solar power in watts generated over the course of a day. The last section is the cumulative energy generated from the microgrid for the day in kilowatt-hours (kWh).

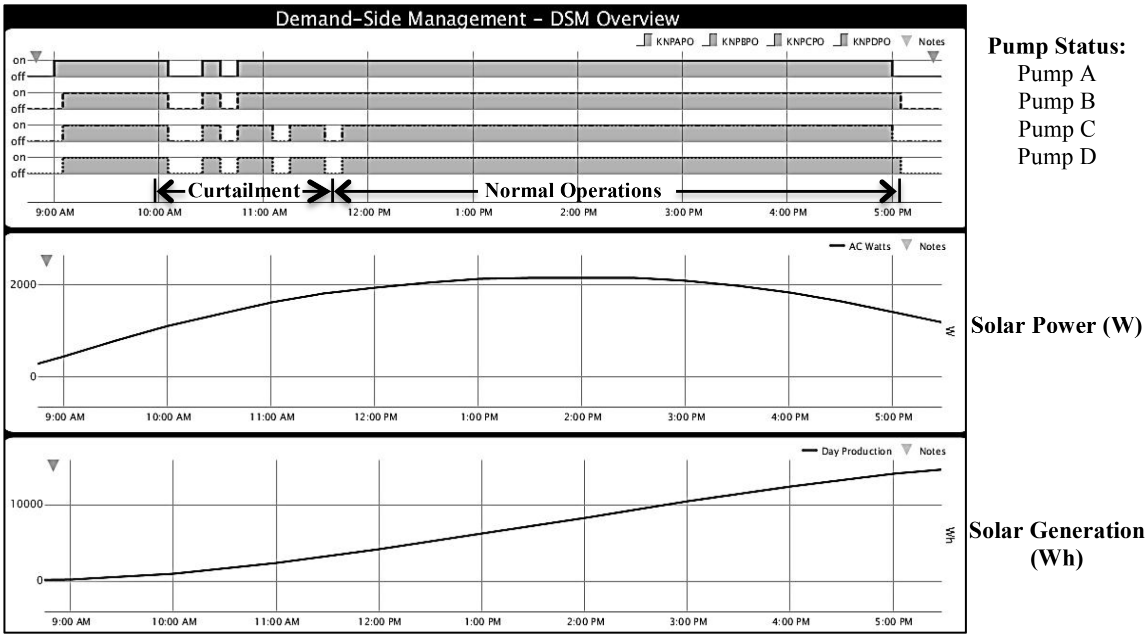

**Figure 5.** DSM Decision Summary for Excellent Generation Day

Figure 5 is an example of an excellent day for renewable energy in the DSM algorithm. The microgrid generation for the day totaled at 14 kWh, but between 9:00 a.m. and 11:00 a.m. there was cloud cover and the power generation was low. The DSM algorithm recognized this and intelligently enabled a curtailment scheme for Pump B, C, and D between 10:00 a.m. and 11:00 a.m. As the day progressed, the DSM algorithm intelligently controlled pumps C and D on a curtailment until 12:00 p.m. when sufficient energy generation was measured and the DSM program enabled normal operations for the remainder of the day.

Figure 6 presents the consumption levels of the thermal process during the excellent supply generation day as kWh versus time of day. The baseline consumption without the DSM program or microgrid is depicted as the solid line, overall consumption with the DSM program enabled is depicted as the dotted line, and consumption with the DSM and microgrid is depicted as the dashed line. During days of excellent generation from the microgrid, the DSM optimally controlled the simulated process depending on microgrid generation and process demand. With the DSM program enabled, overall energy consumption was reduced from 66 kWh to 58 kWh, a 12% reduction. Microgrid supply for this day was 14 kWh, this reduced average overall consumption even more from 58 to 44 kWh, a 29% reduction from the baseline consumption 66 kWh. Overall total electric reduction from the baseline is 22 kWh for this day.

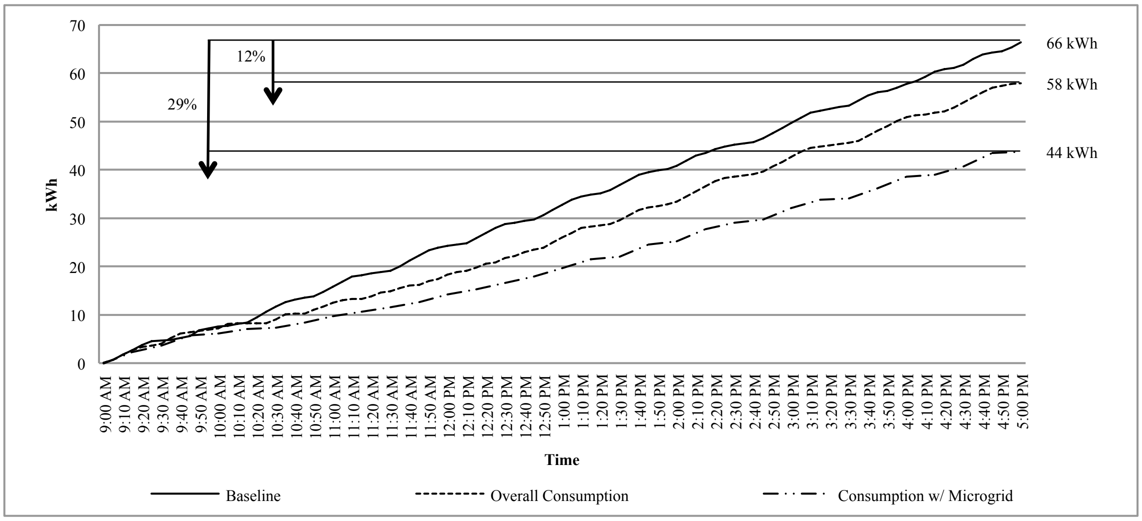

**Figure 6.** Consumption Reduction with Excellent Supply Generation

During days when microgrid generation ranged between 5 kWh and 10 kWh, weather conditions were partly cloudy or cloudy throughout the day. These days were labeled as "Good" supply generation days. Though weather conditions were not ideal, the DSM algorithm intelligently controlled the simulated processes to reduce energy consumption and enabled curtailments due to lower microgrid generation. Figure 7 presents the performance of the DSM algorithm during a day with good generation. As shown in Figure 7, normal operations were enabled from 9:00 a.m. to 12:00 p.m., due to steady microgrid generation. As the day progressed, the DSM program recognized a change in generation at 12:00 p.m., this is noticed by the dip in solar power generation around 12:00 p.m. The DSM algorithm enabled curtailment strategies for pump A, B, C, and D at 12:00 p.m., but supply was determined to be enough to run pump A at normal operations for the remainder of the day after 1:00 p.m. Pump B, C, and D remained in curtailment until 4:00 p.m. when Pump B was ran at normal operations until 5:00 p.m.

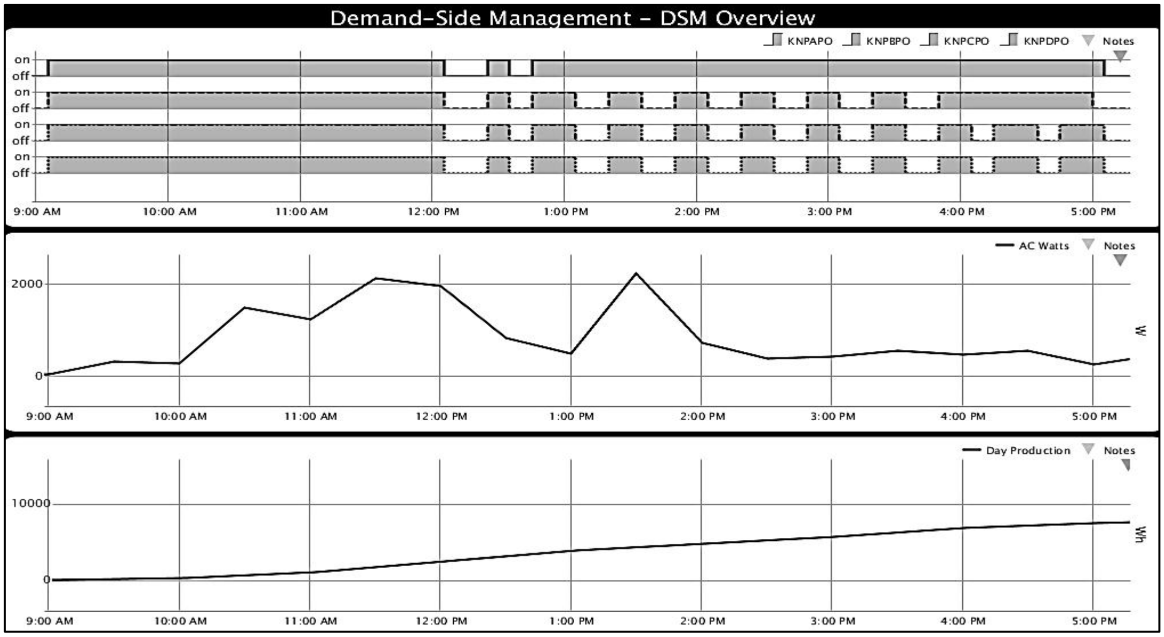

**Figure 7.** DSM Decision Summary for Good Generation Day

Figure 8 presents the consumption levels for the thermal process from Figure 7 above. Despite having lower energy generation than an excellent day, the DSM algortihm continued to optimally control the simulated process and lower energy consumption overall from the utility. With the DSM program enabled, average overall energy consumption was reduced from 66 kWh to 45 kWh. This reduction resulted in a 32% reduction from the baseline. Microgrid supply for the day was 8 kWh, this reduced average overall consumption even more from 45 to 37 kWh, a 44% reduction from the baseline consumption 66 kWh. Overall total electric reduction from the baseline is 29 kWh for this day.

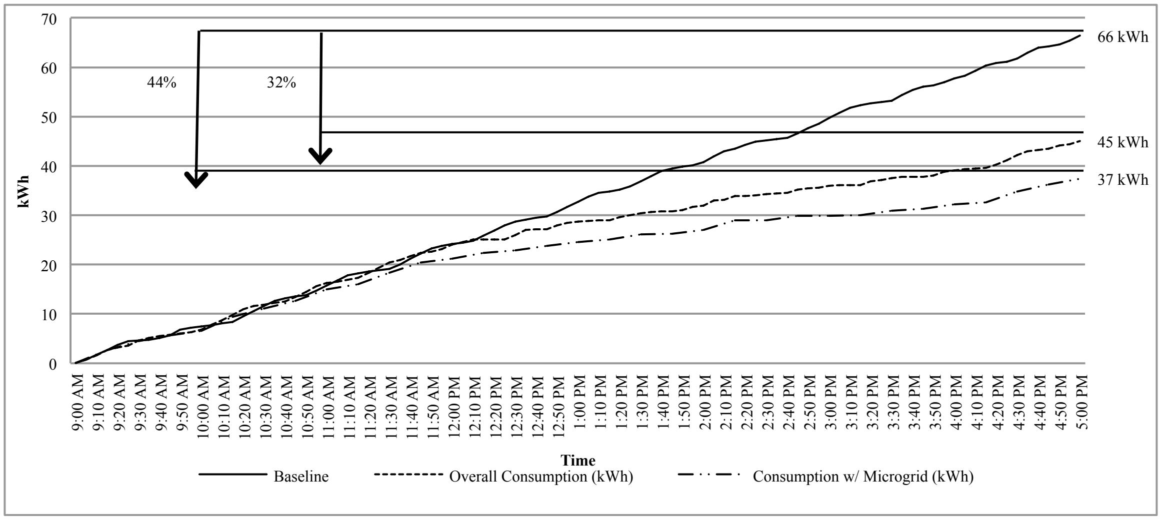

**Figure 8.** Consumption Reduction with Good Supply Generation

During days when microgrid generation supplied less than 5 kWh, weather conditions were mostly cloudy or raining throughout the day. These days were labeled as “Poor” supply generation days. Figure 9 presents the performance of the DSM algorithm during a day with poor generation. As seen in Figure 9, at 10:00 a.m. the DSM program enabled curtailment for all pumps until 1:00 p.m. when pump A was enabled to run at normal operations for the remainder of the day. Pumps B, C, and D continued on a curtailment strategy for the remainder of the day due to the supply not meeting the demand of the process.

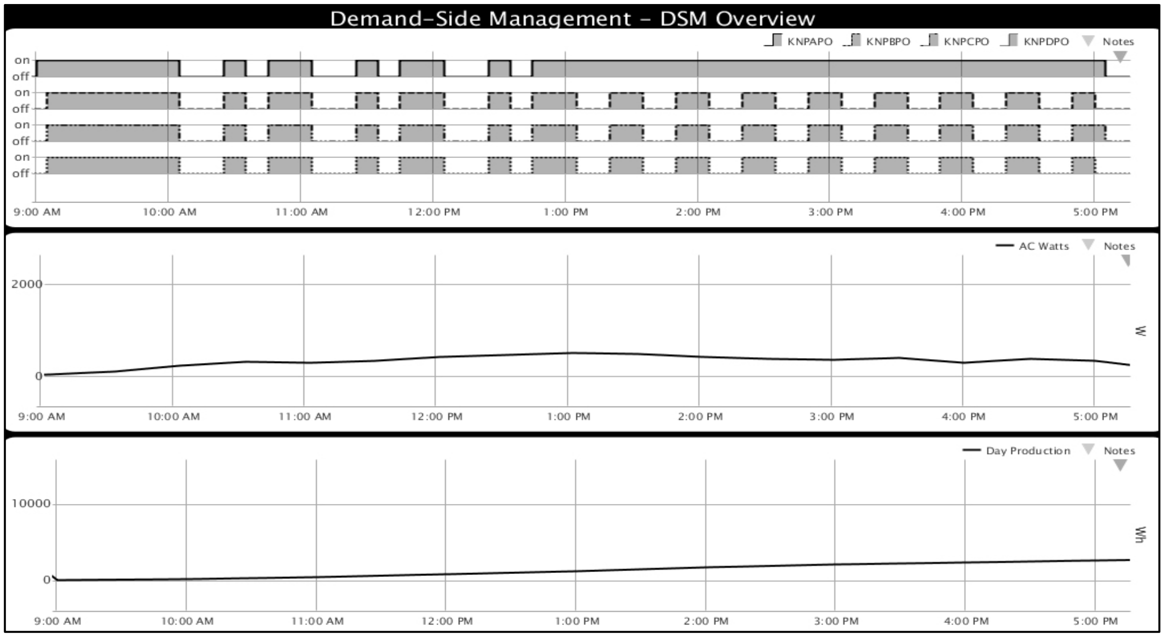

**Figure 9.** DSM Decision Summary for Poor Generation Day

Figure 10 presents consumption levels for the day used for Figure 9. During this day, the overall electrical consumption using the DSM program was reduced to 28 kWh, a 58% reduction from baseline. Microgrid supply for this day was 2 kWh, this reduced average overall consumption from 28 to 25 kWh, a 61% reduction from the baseline.

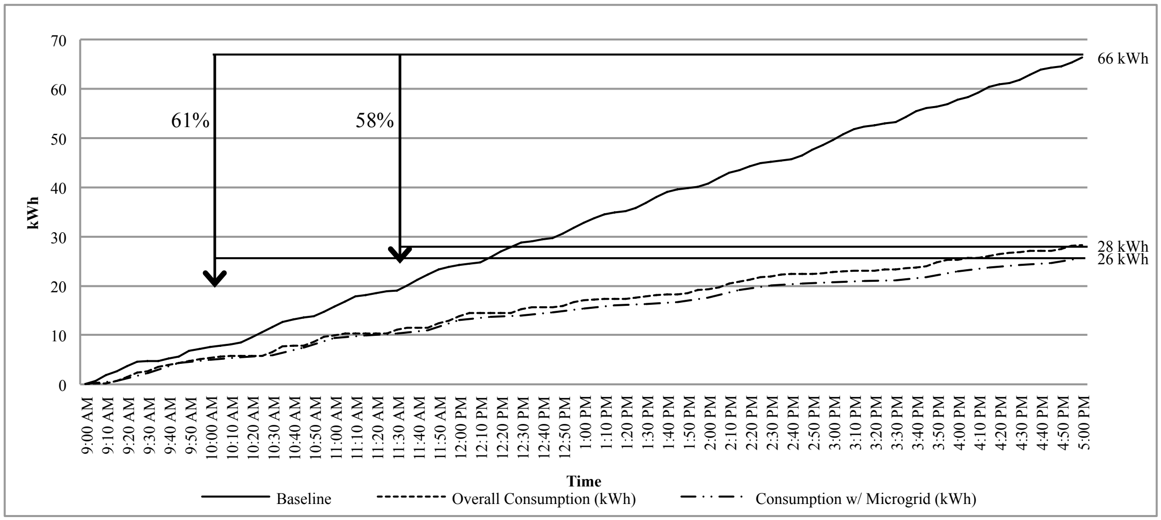

**Figure 10.** Consumption Reduction with Poor Supply Generation

## 5. DISCUSSION

For this research the performance objective was to show that the combination of a microgrid and DSM controls could maintain 70% of manufacturing full capacity. Maintaining 70% of full capacity from a microgrid should be of interest for facilities around the world that are forced to shut down due to poor electrical grid systems. Figure 11 is an effort to evaluate the impact of the microgrid in terms of achieving the 70% goal.

The vertical axis of Figure 11 is Manufacturing Intensity, which is the ratio of the overall consumption for one day with the demand limiting algorithm in operation as compared to manufacturing demand with no controls in place. By definition, Manufacturing Intensity varies from 0 to 100%. The horizontal axis of Figure 11 is Microgrid Availability. This ratio compares the microgrid output for one day as compared to its expected output. The values for Microgrid Availability exceeded 100% on sunny days when the solar resource was higher than normal.

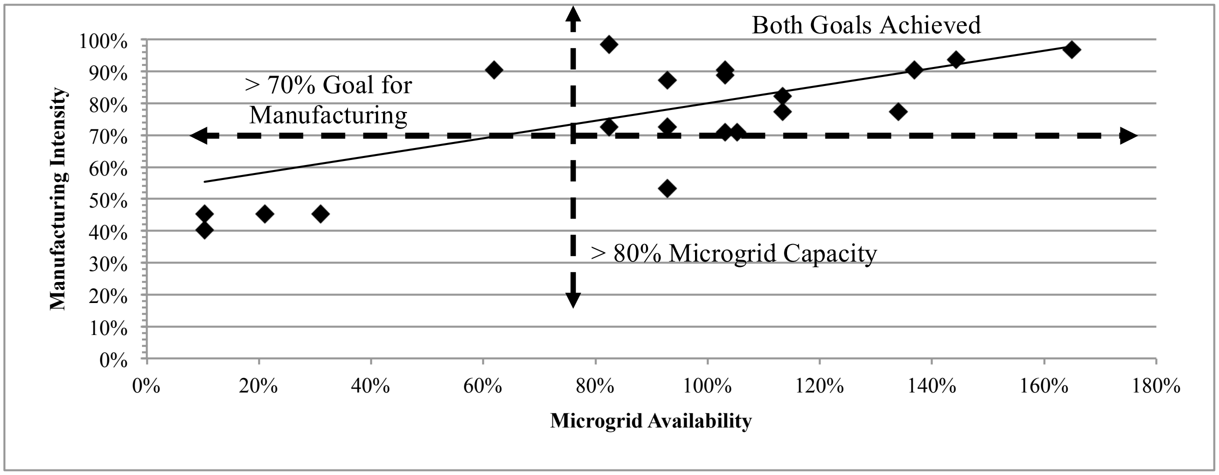

**Figure 11.** Impact of microgrid and DSM on a manufacturing process.

Figure 11 illustrates that the goal of 70% Manufacturing Intensity was achieved when whenever Microgrid Availability was above 80% of its expected output. On days when manufacturing availability was below 80%, the manufacturing intensity was below the target of 70% ranging from 40% to 50%. Not surprisingly, Figure 11 also shows a positive correlation for Manufacturing Intensity as a function of Microgrid Availability. This simply means that it is easier to meet manufacturing goals when the microgrid contributes substantially to the energy mix.

Figure 11 begins to provide insight into the required mix of renewables and DSM to maintain a reasonable level of Manufacturing Intensity, which for this research was set to 70% of maximum. The renewable energy system for this research was rated to provide up to 15% of the total manufacturing capacity, but that only occurred on sunny days. The DSM algorithm provided the buffer to help achieve high levels of Manufacturing Intensity on days when microgrid production was less than optimal. The interaction between renewables and DSM is still being explored. This paper also does not address energy storage which could further enhance Manufacturing Intensity when renewable power is lacking.

## 6. CONCLUSION

The results show that active management of a manufacturing microgrid has the potential for saving energy and money by intelligent scheduling of process loads. As well, data supports that when microgrid availability is above 80% of expected generation, manufacturing intensity stays above 70% of manufacturing full capacity. This data demonstrates to manufacturers that have to shut facilities completely down, due to electrical grid issues, that a microgrid on site with DSM load management, can output products despite being grid-independent. Next steps for this research would be investigating the use of energy storage with the microgrid to see its impact on overall electrical consumption and management of loads.

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