A Heuristic Technique for Scheduling a Customer-Driven Residential Distributed Energy Resource Installation

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Abstract—**This paper introduces a heuristic technique for scheduling a residential DER installation containing photovoltaic arrays and local energy storage, interfaced to the grid through a single phase voltage source inverter. The principal aspect of the technique is aligned with the Smart Grid Initiative in order to provide customer-driven operation of the DER installation, while maximizing the customer's daily profit. The technique is based on the DER installation's ability to sell specified amounts of real and reactive power to the utility grid. The technique is implemented in an algorithm that determines the operating points for the inverter for the next 24 hrs of operation based on forecasts of the residential demand, solar irradiance, and the price of real and reactive power. The validity of the technique is illustrated through an example case study, and compared with the day's operating costs of the same residence without local energy storage, and without a DER installation.**

Index Terms—**Customer-driven, distributed energy resource, distributed generation, Energy and Independence and Security Act of 2007, energy management, heuristic optimization, energy storage, scheduling, Smart Grid Initiative**

I. NOMENCLATURE

ARRA	American Recovery and Reinvestment Act
DER	Distributed energy resource
DG	Distributed generation
DSM	Demand side management
DSR	Demand side response
EISA	Energy Independence and Security Act
HAN	Home area network
LEMS	Local energy management system
PCC	Point of common coupling
PV	Photovoltaic
RPS	Renewable portfolio standard
SOC	State of charge

II. INTRODUCTION

Title XIII of the Energy Independence and Security Act of 2007 – popularly termed the 'Smart Grid Initiative' - was enacted by the 110th United States Congress in order to modernize the transmission and distribution grid of the US [1]. The Smart Grid Initiative includes the following points for the modernization of the grid: increased use of digital control and information technology with real-time availability; dynamic optimization relating to grid operability; inclusion of DSR and DSM technologies; integration of DER including renewables and energy storage; and deployment of smart metering, distribution automation, smart appliances and customer devices [2]. While the move toward the Smart Grid has gained momentum in the US – including allocation of several billion dollars for Smart Grid projects through the ARRA of 2009 [3] – it is imperative that the Smart Grid installations targeting residential customers provide economic justification.

In the US, there are also state-level mandates for obtaining a certain percentage of electricity sales from renewable energy resources, namely through RPS [4]. An example of the impact of such state level mandates is the issuance of the 'million solar roofs' initiative in the US state of California [5]. In light of the Smart Grid Initiative and RPS, it is apparent that customers that install DER would seek to attain optimal operational profits from the installation, while the utilities to which such customers connect may potentially use the DER installations for peak shaving [6]. In another avenue of the Smart Grid Initiative, several computer firms have embarked on developing home energy management software for consumers [7, 8]. Such smart applications are expected to provide timely information and possibly control options to the customer that has installed a smart appliance or a DER in their facility. Smart applications may be fitted with intelligent algorithms for optimal operation of the customer owned DER so as to realize an economic profit by trading services with the utility grid. Other DER application avenues include performing least cost optimizations through Lagrangian optimization [6], and linear programming [9]. However, developing an operational algorithm for a residential DER installation that maximizes the profit of the consumers makes the idea of Smart Grid more attractive. It is in this area that the scope for intelligent systems such as agent technology appears attractive. The technique described in this paper differs from the work in [6] in incorporating a heuristic technique for customer-driven scheduling and considering the trade of reactive power in addition to real power to the grid. In that regard, this paper will address an economic and customer-driven approach for scheduling the operation of a residential

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DER installation – a roof top PV set up interfacing the grid through a ‘smart’ inverter and associated energy storage. The scope of this paper does not include the design, topology, and operation of the smart inverter itself – this is described in [10]. This paper focuses on a heuristic technique for scheduling the operation of the smart inverter for realizing an economic profit from the customer owned DER installation. It is pertinent to note that the work described in the following sections relates to the following points of the Smart Grid Initiative: deployment and integration of DER including renewable sources, DSM, deployment of smart technologies, the incorporation of energy storage and peak-shaving technology, and the ability for consumers to access usage data and have subsequent control options. The authors envision the heuristic technique – or its evolved version – to function as the intelligence of the control systems used for home energy management.

This paper is organized as follows: Section III lists some enabling technologies that are required for this exercise in scheduling the DER installation; Section IV describes the customer-driven DER test system and its salient components; Section V discusses the heuristic technique for scheduling the DER installation; Section VI presents an example case; Section VII provides conclusions; and the Appendix in Section VIII includes relevant data for the example case.

III. ENABLING TECHNOLOGIES

In order for the developed technique to function at the highest level, several enabling technologies must be present, and concomitantly, some necessary assumptions have been made for the purposes of the work described in this paper. Prior to listing the enabling technologies, it is imperative to define the term ‘customer-driven’ as it pertains to distributed energy resources as: an electric power distribution system in which the “*customers install utility compatible generation sources in their homes or facilities; each such distributed resource is an autonomous agent with characteristics that include economic, technical and social responses to system generated signals. Economic responses involve a willingness to generate more (or consume less) in response to a signal, to be willing to supply reactive power, or to participate in frequency regulation. Technical responses of this agent include safe startup and shutdown, while social response involves proper operation under islanded conditions*” [11]. However, in order to realize customer-driven DER, some enabling technologies must evolve into practice.

Specifically, the enabling technologies for the customer-driven DER include: a) necessary enhancements to the existing distribution system, including higher voltage level interconnects, transitioning from a primarily radial distribution topology to meshed, and an accompanying adaptive protective system that can handle bidirectional power flows; b) existence of a market structure that recognizes the DER installation as a fully participating entity; c) progression toward standards for operation of DER that do not preclude the DER from providing voltage support at PCC (the authors acknowledge the safety consideration of existing standards such as the IEEE 1547 in disallowing such an operation in current times [12]); d) proliferation of smart power electronic devices and agent-like control technology for incorporating local control and intelligence to DER; e) availability of prognostic information on weather conditions, dynamic pricing of electricity, load management; and f) ubiquitous installations of smart meters interacting the grid via HAN [13]. The residential DER installation interfacing the grid through a ‘smart’ inverter [10] – which is considered as an ideal candidate for implementing the heuristic technique described in this paper – adheres to the above definition of a customer-driven DER. For completeness, a brief description of the residential DER installation that uses the ‘smart’ inverter from [10] is provided in Section IV.

IV. CUSTOMER-DRIVEN DER TEST SYSTEM

The customer-driven DER installation test system developed in [10] serves to interface a PV array to the grid through a 'smart' inverter and local energy storage. The test system also comprises a residential load (which is partitioned into high priority and non-critical loads), a smart meter, and appropriate interconnections with the utility grid. A block diagram of the test system is shown in Fig. 1 [10]. The PV array, modeled in [10] as a DC link, is assumed to connect to the ‘smart’ inverter through a DC-DC converter which outputs a constant DC voltage. The inverter in [10] is rated at 5 kVA, 120 V, single phase 60 Hz AC voltage source inverter and is characterized as 'smart' because it has the ability to regulate the voltage at the PCC, supply local load as well as utility loads, and incorporate customer preferences in control [10].

For the study described in this paper, a lead-acid battery energy storage system rated at 50 kVAh is assumed to be associated with this customer-driven DER test system. The test system in [10] features a controller that can switch the mode of operation between grid connected and isolated – by employing current control and voltage control, respectively – and specifies real and reactive power outputs based on reference points of operation.

For running the heuristic technique the test system is assumed to possess an intelligent local energy management system (LEMS) [14], that performs the task of setting the necessary operating points and communicating it on an hourly basis to the controller of the test system. The input data to LEMS may include up-to-date information on parameters such as battery state of charge, residential loading forecast, weather information (specifically the solar irradiance for this test system based on PV), net energy flow measurement, and the hourly energy prices for real and reactive power as communicated by the utility. A conceptual block diagram of the paths for energy flow and communication flow assumed in the customer-driven DER test system is shown in Fig. 2. In alignment with the evolving home energy management schemes, the authors contend that this information flow within the customer-driven DER installation may be available for customers’ access via a dedicated account on a communication network (i.e., HAN). The information may pertain to inverter settings, and the inputs (forecasting, real time pricing from utility, smart meter readings), and an hourly breakdown of the operational profit made in a 24 hour period.

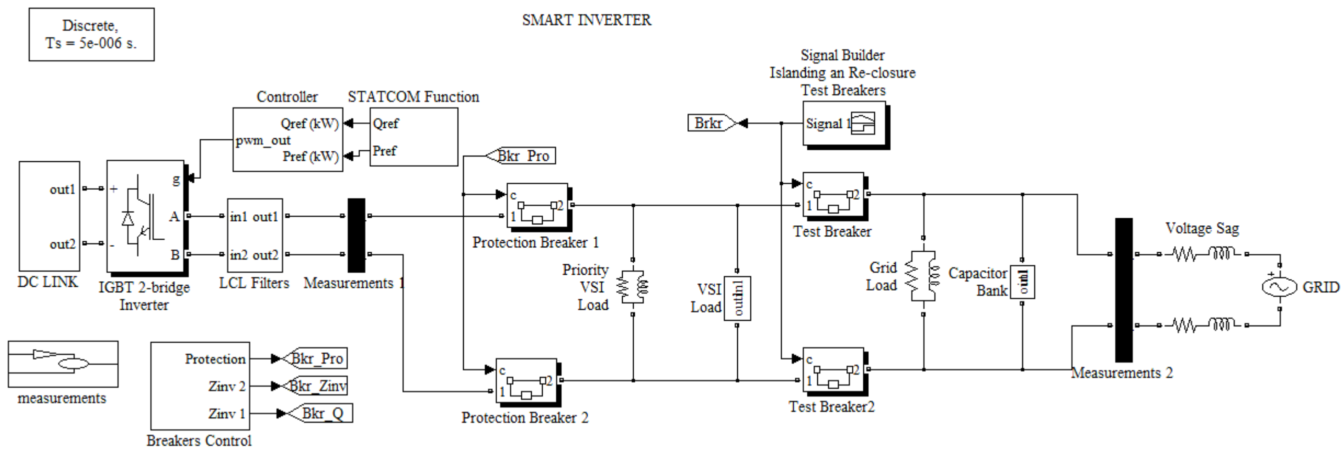

Fig. 1. Block diagram of customer-driven DER test system using 'smart' inverter [10].

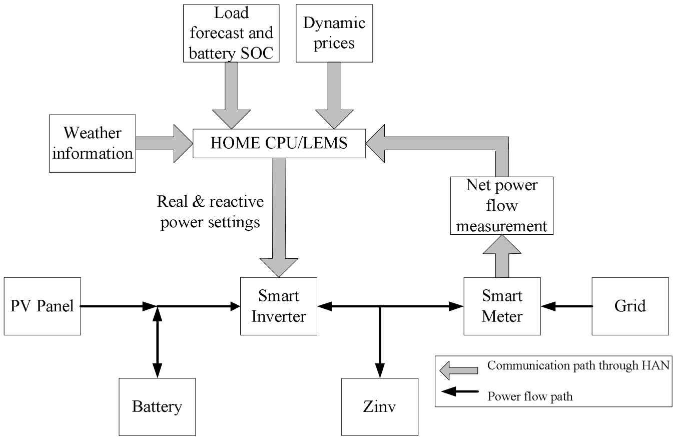

Fig. 2. Assumed DER installation communication path.

V. A HEURISTIC SCHEDULING TECHNIQUE

The heuristic scheduling technique is designed to run once every 24 hours using the forecast information for the following day. The objective of this heuristic scheduling technique is to drive the operation of the residential DER toward a region of operational profit through user inputs – thus contributing to the customer-driven nature of the DER installation. The heuristic scheduling technique is viewed as a framework for incorporating further intelligence to the LEMS for managing the customer-driven DER.

Operating set points are established on an hourly basis and communicated to the 'smart' inverter. The set points include the quantity of real and reactive power to export to the grid, and/or to purchase from the grid. The technique also outputs the quantity of real power that is bought from the grid for storage, as it is assumed that all photovoltaic input is stored to the battery. Furthermore, it outputs the quantity and type of power (real or reactive) that is used directly from storage to supply power to the local load, and/or the utility.

It is assumed that information such as daily set points, expected profits, and overall system information can be accessed by the consumer through the LEMS which may be run on a PC [7]. At this point, the consumer has the option of changing future system set points based on individual preferences. Assumptions have been made that include full accuracy and availability of 24-hr forecasts of solar irradiance, price of electricity based on time of use for real and reactive power, and residential loading information. It is assumed that the price to buy is the same as the price to sell. The utility grid is further assumed to have an infinite demand such that the supply from the local DER is always bought by the grid and the system investment recovery corresponding to the capital cost is not considered. The focus of this heuristic technique is placed on the daily operational profit of the customer-driven DER installation.

A. Description of Zones and Their Operation

The technique divides any 24-hr block into four zones. PV scheduling has previously been based on the insolation, the availability of energy storage, and system loading, [6], [15]. However, in this paper the delineation of the zones is made by a customer-established minimum (P_{min}) and maximum (P_{max}) price threshold for electricity bought and sold. The customer established minimum (P_{min}) is the maximum price the customer is willing to pay to the utility to supply their own storage. P_{max} is the maximum price the customer is willing to pay for electricity supplied from the utility. All rates that fall below the minimum threshold pertain to Zone 1; Zone 2 is defined by hours where the rates fall above P_{min} and below P_{max}. Zone 3 occurs for all hours where the rate is above P_{max}. Zone 4 is different in that it occurs after Zone 3, where the pricing signal is declining by the hour.

A pricing signal is used as the driving function of the heuristic scheduling technique. The pricing signal is generated by comparing the price of real and reactive power for each hour, where the greater value forms the pricing signal. The price of real and reactive power for the example shown in this paper is synthetic data that mirrors a residential demand profile (see Table III in Appendix). Fig. 3 illustrates the various zones in the 24 hour period based on the pricing signal, P_{max} and P_{min}.

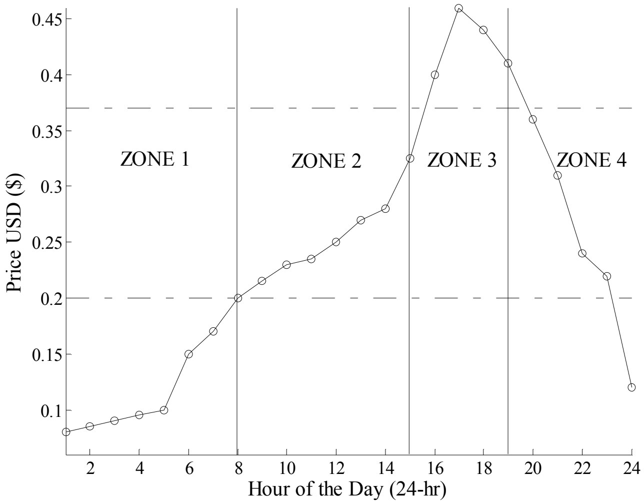

Fig. 3. Ideal pricing signal trend, including zonal delineations

B. *Zonal Operation*

For the following description of the heuristic technique based on zones of operation, it is assumed that the customer has chosen a maximum depth of discharge of 60%, in order to protect the life of the battery [16]. To further protect the life of the battery, the charging rate of the lead acid battery was limited based on the SOC.

In *Zone 1*, the operation of the test system is defined by using the available PV input and scheduling electricity purchase from the grid in order to supply the local load. Moreover, electricity is purchased from the grid in order to charge the battery to 100% during this zone. Nothing is scheduled to be sold from the customer installation to the grid during this zone. In this example, it is imperative that at the end of this zone, the SOC is at 100%.

During *Zone 2*, greater insolation levels are experienced than during Zone 1 because Zone 2 typically occurs from late morning to early afternoon. It is assumed that the DER is installed in a location similar to Golden, Colorado (coordinates 39° 44′ 49″ N, 105° 12′ 39″ W). The goal during this zone is to maintain 100% SOC, therefore using the immediately available PV input to supply the local load. If there is not enough immediate PV input to supply the local load fully, then the difference is scheduled to be purchased from the grid. It is required to maintain a 100% SOC during this zone, so that it can be utilized in the most expensive zone, Zone 3.

In *Zone 3*, when the prices of energy are high (according to rate based on time of use model), the first priority of the technique is to supply the local load completely using the PV input (if available) and through the use of the battery. Once the local loads have been supplied, the remaining energy available from the battery is scheduled to be sold at the most expensive hour to a maximum of 5 kVAh. This continues at descending prices until the SOC has reached 60%, at this point no further sale of electric energy from the customer-driven DER is scheduled. In the case that the SOC reaches the customer pre-established minimum of 60% before the local load for each hour is supplied, then the heuristic method will require the battery to serve the local load. The greatest priority will be given to the hour with the greatest energy price, and so forth in decreasing priority until the SOC reaches 60%. After the battery has been depleted to its minimum (i.e., 60% SOC in this case), then the local load for the remaining hours will be served from the grid, and there is no more available energy to sell during this day's operation.

Zone 4 typically follows Zone 3, when the pricing signal hits the P_{max} threshold on the descent. It is fair to assume that the SOC at the start of Zone 4 is most likely depleted to 60%. However, if there is any more energy available for supply in this zone, it is scheduled to be used during the most expensive hour in Zone 4; this is progressively performed until the SOC reaches its minimum of 60%. Afterwards, the local load is fully supported by electricity purchased from the grid, and nothing is scheduled for sale during the remainder of Zone 4. As the pricing signal crosses the P_{min} threshold on the descent, the heuristic technique resets to a new cycle starting at Zone 1.

VI. AN ILLUSTRATIVE CASE STUDY

The following is an example of the algorithm being run just before the midnight hour on the LEMS, such that the system set points are established for the next day starting at the midnight hour. First, the relevant input data will be presented, followed by the algorithm output. All input data is synthetic unless otherwise noted and given in the Appendix. The output data are supplied later in this section.

Figs. 4-6 display the local residential demand (Z_{inv}) and PV availability, energy prices and resulting price signal, and the maximum possible energy storage available to the battery dependent on its state of charge. The input PV data is based on solar irradiance data for Golden, CO on July 4th 2005, using a 40 m^2 solar array with an overall efficiency of 12% [17]. Figs. 7-8 show the outputs of the algorithm, namely the resulting battery state of charge, and the energy bought from and sold to the grid. Table I displays a zonal breakdown of the system's operation.

A. *Input Data*

As can be seen from Fig. 4, for a typical sunny day in Golden, Colorado the available input from the PV array is greater than the local residential demand. In this case, from 8am until 4pm. Looking ahead at Fig. 8, that excess energy is sold to the grid. The pricing signal given by Fig. 5 for this day's operation is an indicator of whether real power or reactive power is more profitable during each hour. The maximum possible storage per kVAh is dependent on state of charge and is constrained in order to protect the life of the battery. The trend in Fig. 6 is a result of synthetic data, but in practice will be established by the customer's own local energy storage parameters.

B. *Results*

The following results are the outputs of the heuristic technique and can be monitored and/or changed from the LEMS by the consumer. As seen in Fig. 7, the battery SOC is scheduled to increase rapidly in the early hours of the morning; after 8am, the PV input is greater than the local demand such that the immediately available PV input may be scheduled to supply the load completely. The state of charge is expected to decline after 5pm, because it is scheduled to operate at its maximum 5kVA during the peak hours of Zone

3. The SOC will be held at 60% by 8pm in Zone 4, such that for the remaining four hours of operation the local load is scheduled for being supplied by the grid.

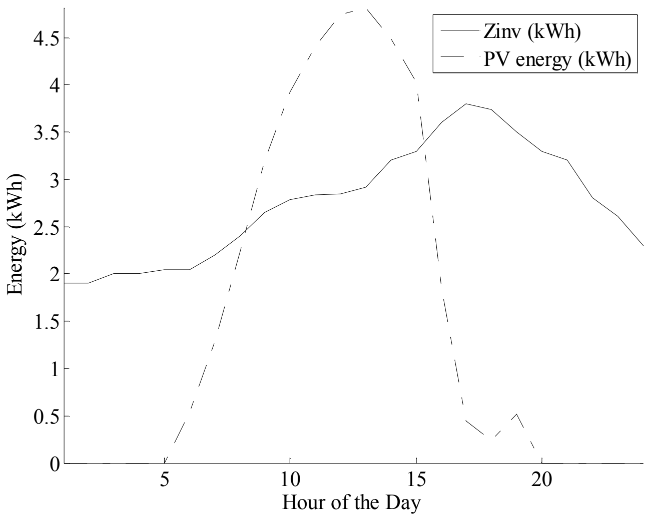

Fig. 4. PV energy available compared with the local inverter demand (Zinv). PV data is given for July 4th, 2005 from [17].

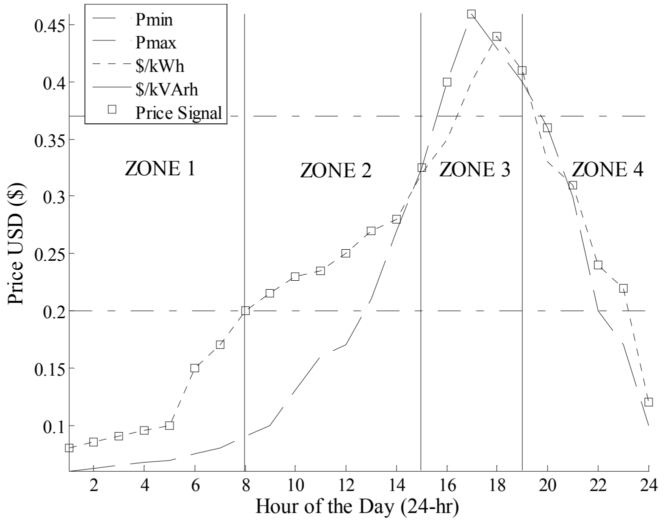

Fig. 5. Synthetic data of price for real and reactive power over a 24 hour period, and the resulting price signal.

An example of the feasibility of the heuristic technique for scheduling the customer-driven DER can be seen from Fig.8. For the example data used in this paper, it is observed that in the hours of traditionally higher overall grid demand, the residential DER installation is able to supply itself. Moreover, in this case it also has enough energy to sell back to the grid, thus alleviating a small portion of the stress on the utility grid during these hours. However, this is not axiomatic of the technique; rather, this example illustrates a feasibility of such scheduling if certain favorable conditions and enabling technologies are present. One of the future works in this area pertains to handling data that may not necessarily adhere to the ideal trends shown in this example.

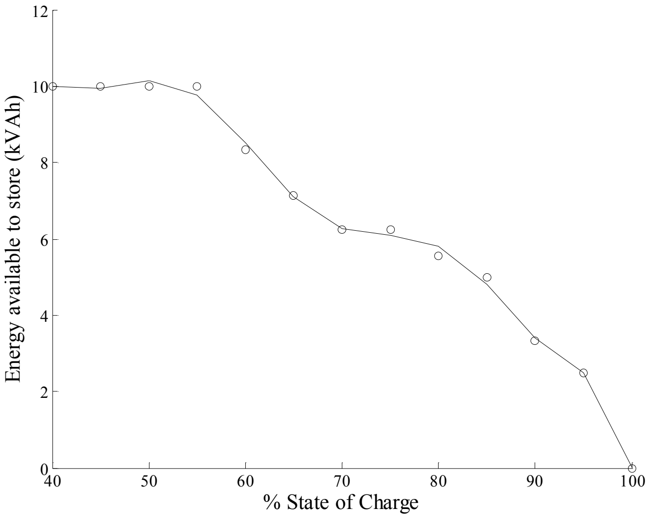

Fig. 6. Maximum energy storage to the battery during a one hour period according to its state of charge. The charging rate is limited in order to protect the battery.

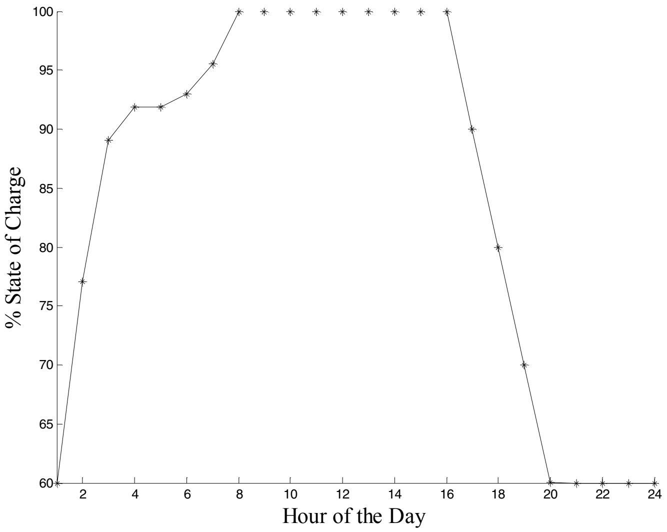

Fig. 7. Resulting battery state of charge

For the given example where the customer was without a DER and associated energy storage installation, the total cost for consuming electricity at the given rates and local load profile is computed at $16.84 USD. For further comparison on the same day's operation where the DER installation did not include local energy storage, and the system used the available PV energy, and sold any excess as real or reactive power (depending on which was more profitable for that hour) to the grid, would result in an operating cost of $7.29 USD.

As seen in Table I, the total cost of electricity consumption by the same customer in the presence of DER with local energy storage capacity and the heuristic technique for scheduling is 2.35 USD (cost). There is a negative profit (i.e., cost) associated with Zone 1 of -3.37 USD because the energy is purchased from the grid to supply both the local load and the charging of the battery. Due to the day's PV input, no energy was purchased from the grid during Zone 2 because there was sufficient energy to supply the load; the profit experienced during Zone 2 is derived from selling the excess

PV input to the grid. Zone 3 also sees a profit because there is enough storage and a small amount of PV energy to both supply the local load and still have an excess to sell to the grid. The increased cost of Zone 4 results from the depletion of storage and no available PV input, thus all of the local load must be purchased from the grid. In this example, it is seen that a local scheduling technique for the DER installation has moved its operation into a region of economic profit for a 24 hour period.

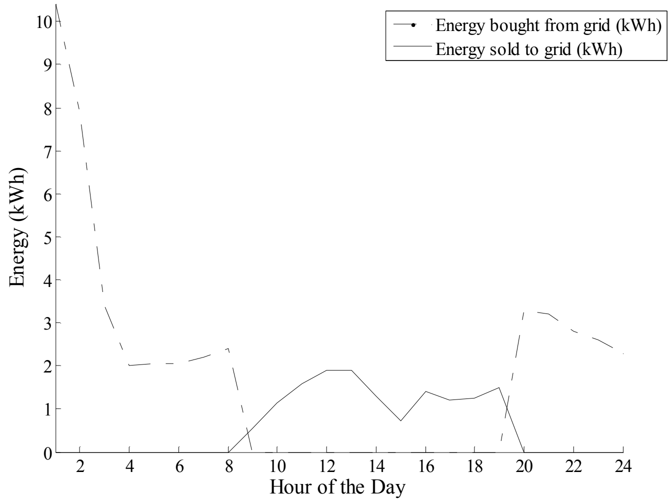

Fig. 8. Comparison of the energy bought from, and sold to the grid during a 24-hr period.

TABLE I. ZONAL DECOMPOSITION OF THE TEST SYSTEM OPERATION

Zone	PV input (kWh)	Total energy bought from grid for storage (kWh)	Total energy bought from grid (kWh)	Real power sold to grid (kWh)	Reactive power sold to grid (kVArh)	Profit (USD)
1	4.06	15.93	32.44	0	0	-3.37
2	29.60	0	0	9.07	.722	2.33
3	3.05	0	0	5.36	2.60	2.29
4	0	0	14.21	0	0	-3.60
Total	36.71	15.93	46.65	14.43	3.32	-2.35

VII. CONCLUSIONS

Developing a local energy management system for residential DER installations is necessary as distributed generation penetration increases through the future. The heuristic technique shown in this paper is tailored to give consumers specific control options for their system, thus aligning itself with the Smart Grid Initiative. Making a DER installation profitable for the customer is important to encourage and provide incentive to the customer for installing such a system in his/her residence. An example case study accompanying the heuristic technique is used to establish the possible economic profit for the customer-driven installation with energy storage. This heuristic technique is envisioned to be resident in the intelligent controls of the customer-driven distributed energy resource installation.

VIII. APPENDIX

The following Table II represents the solar irradiance data directly reproduced from [17]. Table III represents the synthetic data generated for the local residential demand, and the utility pricing of real and reactive power.

TABLE II. PV ARRAY ENERGY INPUT GIVEN BY [17] FOR GOLDEN, COLORADO ON JULY 4TH, 2005. PV ARRAY IS 40 M^2 WITH AN OVERALL EFFICIENCY OF 12%

Hour of the day	SUNY GLO (Wh/m^2)	Hour of the day	SUNY GLO (Wh/m^2)
1:00	0	13:00	1004
2:00	0	14:00	935
3:00	0	15:00	838
4:00	0	16:00	384
5:00	0	17:00	93
6:00	112	18:00	51
7:00	268	19:00	108
8:00	466	20:00	0
9:00	665	21:00	0
10:00	817	22:00	0
11:00	918	23:00	0
12:00	989	24:00	0

TABLE III. SYNTHETIC INPUT DATA FOR THE OPERATION OF THE DER INSTALLATION ON JULY 4TH, 2005 INCLUDING THE RESIDENTIAL DEMAND, REAL AND REACTIVE POWER PRICING

Hour of the day	Residential demand (kW)	Price of real power (USD/ kWh)	Price of reactive power (USD/ kVArh)
1:00	1.900	0.080	0.060
2:00	1.900	0.085	0.062
3:00	2.000	0.090	0.065
4:00	2.000	0.095	0.067
5:00	2.050	0.100	0.069
6:00	2.050	0.150	0.075
7:00	2.200	0.170	0.080
8:00	2.400	0.200	0.090
9:00	2.650	0.215	0.100
10:00	2.780	0.230	0.130
11:00	2.830	0.235	0.160
12:00	2.850	0.250	0.170
13:00	2.920	0.270	0.210
14:00	3.200	0.280	0.270
15:00	3.300	0.320	0.325
16:00	3.600	0.350	0.400
17:00	3.800	0.400	0.460
18:00	3.740	0.440	0.430
19:00	3.500	0.410	0.400
20:00	3.300	0.330	0.360
21:00	3.200	0.310	0.300
22:00	2.800	0.240	0.200
23:00	2.610	0.220	0.170
24:00	2.300	0.120	0.100

IX. ACKNOWLEDGEMENT

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XI. BIOGRAPHIES

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