Economic Analysis of Home Photovoltaics System: Extreme Weather Case Study

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Abstract—A case study of the electric usage and cost of residential households under severe weather conditions is presented in this article. Extremely hot weather in Texas led to a sharp increase in electric usage at the local power grid, which necessitated a corresponding increase in price. For the residential households installed with Home Photovoltaics (PV) System, the solar power could provide a strong support to keep the utility electricity cost from this price surge. Additionally, extra solar energy could help a neighboring household avoid most of the abnormal electricity price. Matlab simulation results also indicate that this electric energy interaction between neighbors can reduce the energy cost of the household with the Home PV System.

Index Terms—Home PV System, residential household, electric usage, solar power

I. INTRODUCTION

The temperature in Texas, USA climbed up to 38 degrees Celsius (100.4°F) on August 12, 2019. Dallas, the most populous city, had a temperature exceeding 38.3°C [1]. Under such heat, Texas's electricity consumption had also set a historical record. Due to insufficient power reserves, the shortage of electricity consumption was severe. On the 12th, all-time peak demand reached 74,531 MW between 4 and 5 p.m. The electricity price of the Texas power grid skyrocketed to $6,537.45/MWh, which was 360 times more than usual [2]. Under such extreme weather conditions, the remaining capacity and stable operation of the power grid were subject to severe tests. The sharp increase in electricity prices seriously affected the normal use of electricity by local residents.

For a household installed with a Home Photovoltaics (PV) System, the situation could be entirely different. In sunny weather, the dependence on external electricity (the utility) would be greatly reduced. It could even achieve fully self-use if the solar power system has proper generation capacity. In addition to excessive heat, full sunshine made the condition optimal for use of household solar power.

II. ELECTRICITY COST WITHOUT HOME PV SYSTEM

Simple calculations for a household without Home PV System were performed using the northern part of Texas (where Dallas is located) as an example. All profiles of electric usage are from Electric Reliability Council of Texas (ERCOT) website [3]. The datasets are all in quarter-hour format. For the convenience of further calculation, the data were converted into hourly format.

For 24 hours' load L_m ($m = 1, 2, \cdots, 24$), a quarter-hour load is L_{mn} ($n = 1, 2, 3, 4$) in kWh, where

$$L_m = \sum_{n=1}^{n=4} L_{mn}. \tag{1}$$

ERCOT also provides quarter-hour settlement price (in $/MWh). However, residential customers need to pay the Transmission and Distribution Utility (TDU) delivery charges, as well as other fees and charges. Based on the load profiles, the average residential customer (single household) had an electric usage more than 2000 kWh in August. The minimum average price in this situation is ¢14.4/kWh for August under normal Real-Time Settlement Point Prices (RTSPP) [4]. For extremely high volume electric usage such as on August 12,
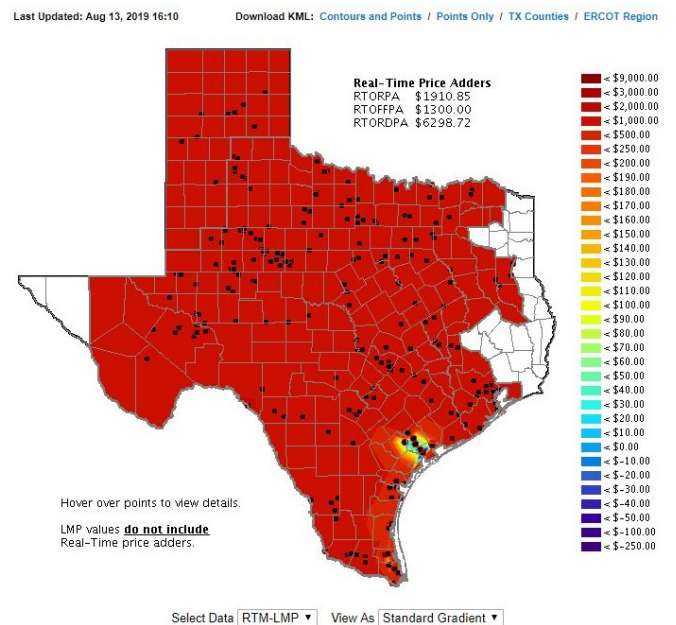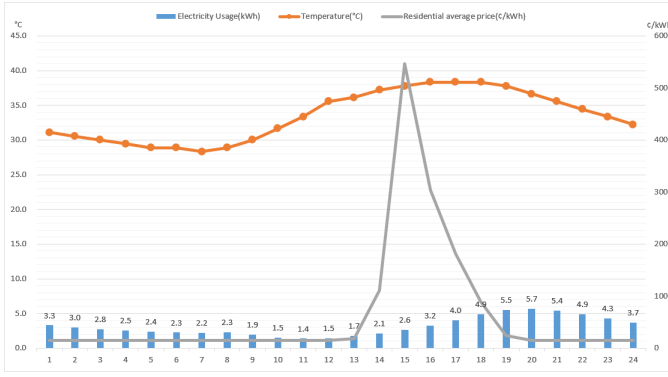

Fig. 1. ERCOT price map

Fig. 2. Hourly electric usage and average price with temperature on Aug 12 in northern Texas area.

Fig. 3. Block diagram for household solar network.

the average price per kWh may vary depending on the hourly RTSPP.

For hourly price P_m ($m = 1, 2, \cdots, 24$), a quarter-hour price is P_{mn} ($n = 1, 2, 3, 4$) in $\$/MWh$, where

$$P_m = \frac{\sum_{n=1}^{n=4} P_{mn} L_{mn}}{L_m}. \tag{2}$$

After data processing, the hourly electric usage and average price with the temperature value is illustrated in Fig.2.

With the hourly average price P_m and electric usage L_m, the day cost can be obtained by

$$Cost = \sum_{m=1}^{m=24} P_m L_m. \tag{3}$$

This calculation shows that the residential customer should pay \$46.06 for the total electric usage on Aug 12.

III. RESIDENTIAL HOUSEHOLD WITH HOME PV SYSTEM

A. Network Configuration

For the modern household solar network, the illustrative configuration block diagram is shown in Fig.3, whereas the inputs are houses with PVs installed on the rooftops and backyards, *etc*. The basic concepts are three-fold:

1) The house is connected to the general power grid, but instead of primary power source, the power grid serves as auxiliary power supply for the household use;
2) Intelligence PV inverter is installed and tuned to "Power Line Communication" topology;
3) The utility price is degraded down such that the self-generated PV power would compensate for the electricity price baseline.

Considering this topology, Fig.3 can therefore be understood as the power-estimation system, the PLC/HMI logic module segregates the power into two categories: 1) power from grid, where the house is the user; and 2) power from PV, where the house is both user *AND* supplier. The battery controller and battery-set serve as uninterruptible power supply (UPS) as system power back-up. A typical PV household-use intelligent inverter topology is shown in Fig.4. The operating PV panels
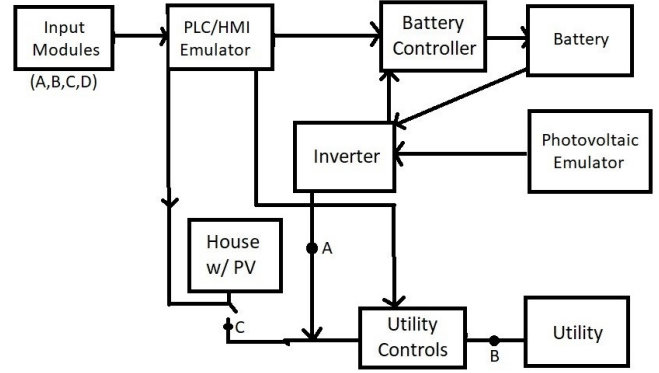
are directly connected to the DC switches. Since for the DC-side high-speed switching is not required, the switches can be simple SiC MOSFET or N-Channel JFET. After the DC switches, current flows down to the DC surge protector for mitigating unexpected DC voltage surges that may be hazardous to the inverter components. The EMI filters are inserted in both DC- and AC-side of the inverter in order to side-loop the common-mode (CM) components in the circuit. The CM current usually comes with the high-edge rates of switching and its inherent parasitic impedance. This circuit quantity is considered as the intrinsic circuit behavior that can be limited or mitigated via different means, the most common and economic way is to add CM choke between phases [5]. The MPPT in Fig.4 is Maximum Power Point Tracking, which is a power quantity given by

$$P_{\text{mpp}} = V_{\text{mpp}} \times I_{\text{mpp}} \tag{4}$$

$$P_{\text{opt}} = f_f \times V_{\text{oc}} \times I_{\text{sc}} \tag{5}$$

$$V_{\text{mpp}}(T) = V_{\text{mpp}}(T_{\text{ref}}) + \mu_{V\text{mpp}}(T - T_{\text{ref}}) \tag{6}$$

where that P_{mpp}, V_{mpp} and I_{mpp} represent the maximum power point power, voltage and current, respectively. Eq. (4) is derived directly from Ohm's Law; P_{opt} is the optimal power under optimized condition. It normally appears in the manufacturer's note; f_f is defined as fill factor representing the ratio of maximum obtainable power to the product of the open circuit voltage V_{oc} and short circuit current I_{sc} [6]. The inverter is designed by a set of vertically placed power electronic switches. The purpose of having output filter is to block high-frequency components of the AC current. It could be realized by either a π- or T-circuit. The output isolator serves as a current barrier that further blocks CM current generated by the gating signal at switches, and mitigates or even eliminates undesired $\mathrm{d}v/\mathrm{d}t$ transients from switch self-oscillation. Before transferring to the outside, the AC surge protector helps side-looping high-frequency components in the current such that the reactive power can be controlled under regulatory limits.

Since the DC power measured directly from PV panels is largely determined by weather conditions such as solar irradiance, wind direction and velocity, ambient and panel tem-
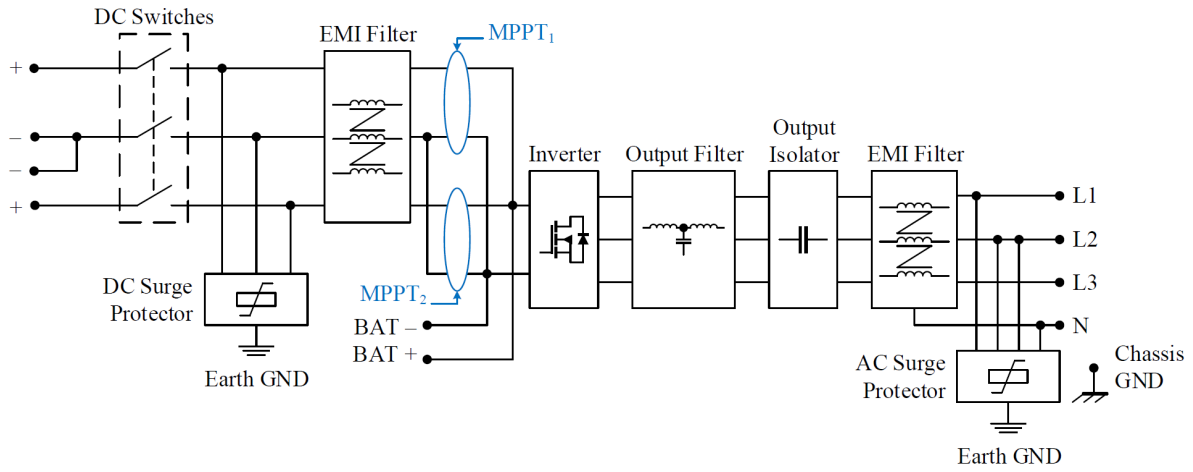
Fig. 4. Topology of a typical PV household-use intelligent inverter

peratures, it is unavoidable to have reactive power transmitted in the AC-side of the inverter. According to [7], the VAR-power variation in the standard 220 kV power grid should not exceed the limit of 0.5%. Thus a static var generator (SVG) is integrated in most of the commercial intelligent inverters.

For the Power Line Communication topology, the core concepts are: 1) discrete PV arrays are arranged by the unit per household; 2) generated power from PV arrays has the priority of satisfying consumption of its own household; 3) if the PV has "excess power", the remainder will be supplied to the neighboring households; 4) if there is no excess power, households will be able to buy power from external power source. The "from-to" process of 3) and 4) describes a trade-off between the prices of selling and buying. Normally in a sunny weather more PV power is generated than consumed. Since arrays from house to house are not separated electrically, the discrete topology of PV arrays only yields a geographical distribution rather than segregation between systems. In this case, a balanced operation strategy needs to be negotiated for a non-zero-sum outcome. An actual field test data shown in Fig.5 illustrates single-day power output chart comparing time-of-the-day as well as solar irradiance data from the 10 MW discrete household power plant at Bayan Nur, Inner Mongolia, China (coordinates 41.01N,107.18E). The peak hours in Fig.5 is roughly between 11:30 to 14:30, which is reasonable considering the solar irradiance reaches maximum in a day at the times around noon. The peak output power does not necessarily related to peak power demand, this time-difference creates a peak load shifting scenario such that the household can contribute their PV power onto the grid during noon time while earning compensate electrical price; while the rush hour of power demands, the load of power grid is increasing which causes the price rising, then the same household choose the power from either extracting local battery, or purchasing from the grid, or both based on the actual demands.
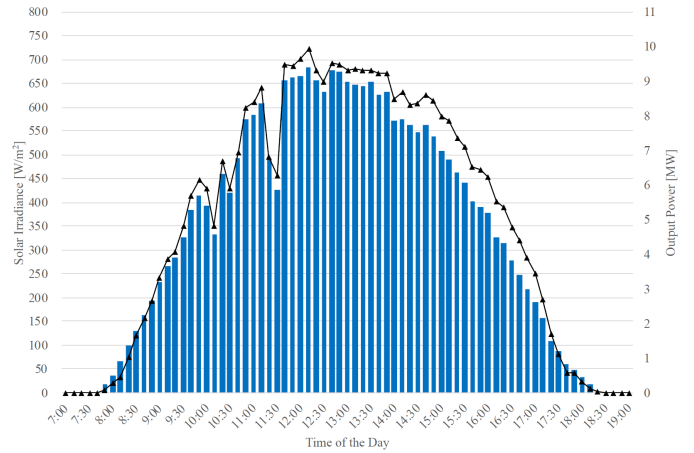

Fig. 5. A one-day power output with respect to time of the day and solar irradiance

B. Electricity Cost Analysis

The National Renewable Energy Laboratory offers the PVWatts Calculator tool to estimate the energy production and cost of energy of grid-connected photovoltaic energy systems [8]. It can generate a solar power output scenario based on weather data of locations and the PV system specifications.

For a household installed with 8 kW solar panel system and located in the Dallas area, the estimated AC power output (blue bar) is shown in Fig. 6.

Considering that August 12, 2019 is a weekday (Monday), the average energy usage between 9 am to 4 pm is relatively lower than during other hours in the day. Within these hours, solar power output is higher than electric load. During these hours, the extra solar power output can be used to charge the energy storage battery.

Assume the maximum capacity of the battery is 10 kWh, and before sunrise, the battery has reached the depth of discharge (DoD) of 90%, only 1 kWh is left in the battery and 9 kWh needs to be charged. Starting from 9 am, the
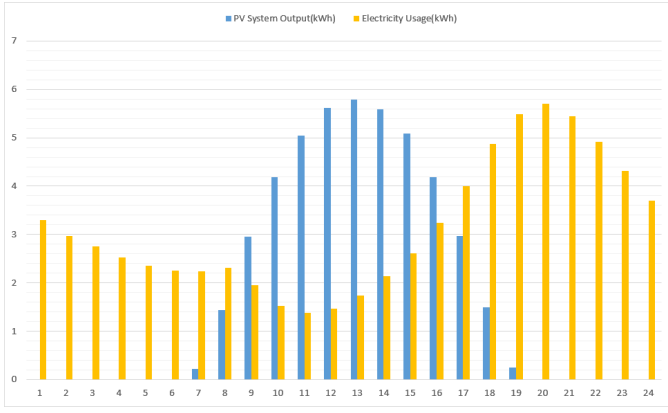
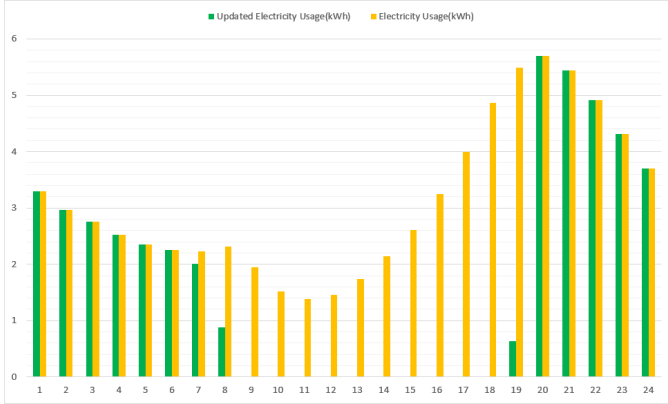Fig. 6. Hourly solar energy output compared with electric usage.

Fig. 7. Updated hourly utility energy consumption compared with electric usage.

PV output has enough remaining power to charge the battery, which will be fully charged before 12 pm. Starting from 5 pm, the battery is needed to balance the electric usage. After 7 pm, the battery reaches DoD. At this point, PV system also ends its generation for the day. This house now relies on utility energy again. However, from Fig. 2 it can be seen that the price increase diminishes after 7 pm. Therefore, with the Home PV System, this residential household can effectively avoid the electric price surge impact. Fig.7 illustrates the updated utility energy consumption.

Applying Eq.3, the updated electric cost for this residential customer is $5.54 for the day, leading to over $40 in saving.

IV. HOME PV SYSTEM POWERING TWO HOUSEHOLDS

In a certain time period of a day, extra solar power may be supportive to a neighboring household beyond self-usage, which is strongly indicated from Fig. 6. Assume there are two households, House 1 (H_1) and House 2 (H_2). H_1 has the Home PV System installed and H_2 has similar load profile as H_1. H_1 is willing to sell excess power to H_2 with a competitive price P_{NG}, which is normally lower than the utility electric price P_m. P_{NG} can be negotiable, yet once settled, it acts like a contract. For H_2, on one hand, this agreement with H_1 would always bring lower energy cost.
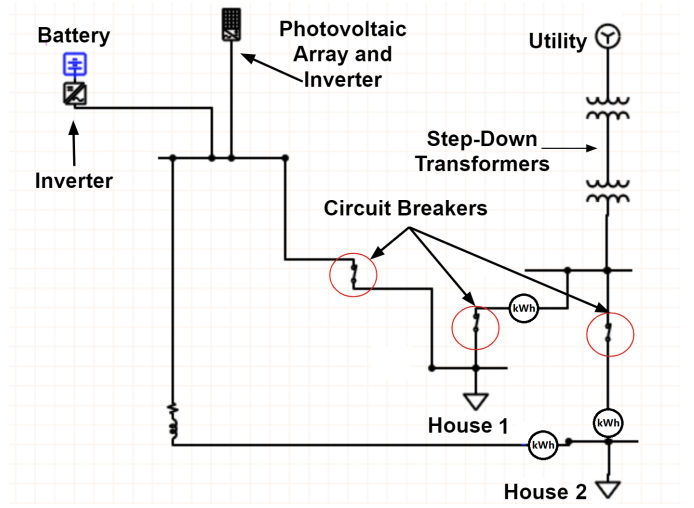

Fig. 8. Two households nanogrid network structure schematic diagram.

On the other hand, even if the power from H1 may not be enough to cover all energy consumption at all time, it could still reduce the risk to the electric price surge at a critical point. The two houses with Home PV System are connecting as a nanogrid which is demonstrated in Fig.8.

Since the power flow is from H_1 to H_2, H_1 has the ability to determine the proper operation strategy. In order to minimize the cost and maximize the profit, there are three principles. Firstly, the operation strategy should be hourly adjusted, based on different electric usage scenario. Secondly, for H_1, solar power should always satisfy self-usage before supporting H_2. This is because, H_1 is selling cheaper electric power than the utility. Thirdly, battery energy storage is not for sale since the previous analysis indicates that, battery energy storage is not enough for self-usage to support H_1 between sunset and sunrise.

A. Scenario 1: Solar power output is smaller (or equal) than H_1 power consumption

When the solar power is insufficient to support the power consumption of H_1, it should consume the energy combination of both solar power and battery storage. The utility power should fill the remaining power gap. In this situation, H_2 can only use utility power, since H_1 has no extra solar power for H_2.

Utility electric usage for H_1 and H_2,

$$U_{H1} = max(H_{1m} - (Batt - Batt_{DoD}) - PV_m, 0) \quad (7)$$

$$U_{H2} = H_{2m} \quad (8)$$

Where

H_{1m} and H_{2m}: hourly energy consumption of H_1 and H_2

$Batt$ and $Batt_{DoD}$: battery current storage and battery storage at DoD
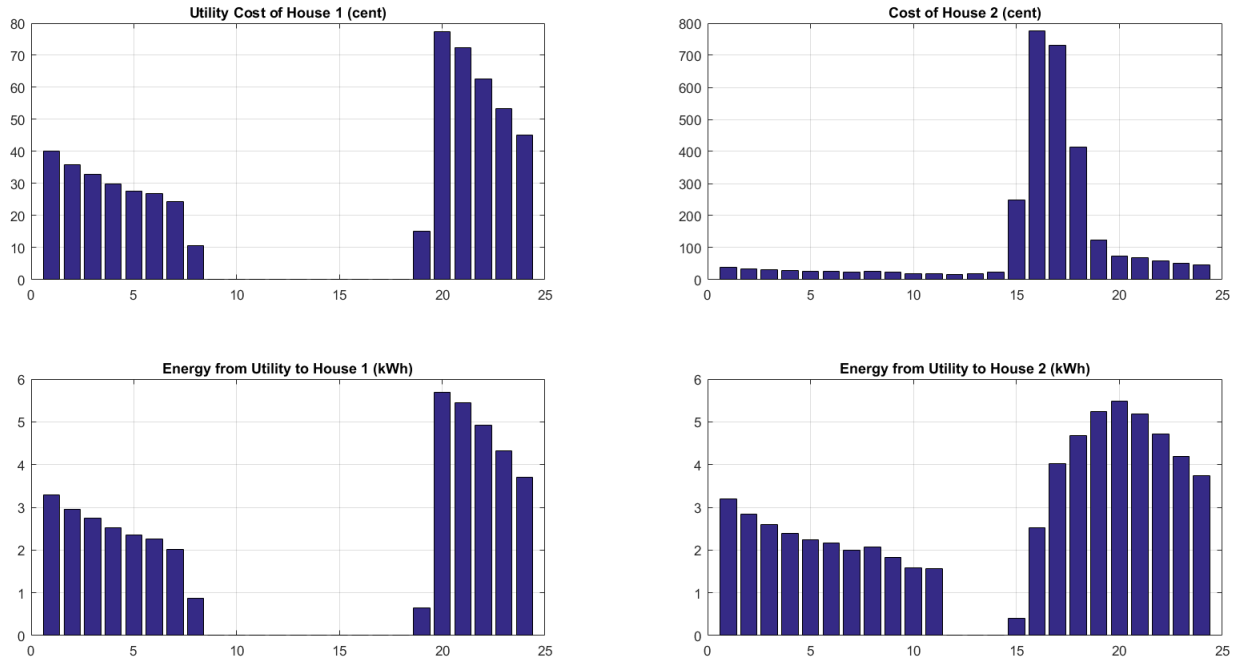
PV_m: hourly solar power output.

Fig. 9. Utility electric usage and cost for H_1 and H_2.

Hourly electric cost of H_1 and H_2

$$Cost_{H1} = U_{H1}P_m \tag{9}$$
$$Cost_{H2} = U_{H2}P_m \tag{10}$$

B. Scenario 2: Solar power output is greater than H1 power consumption, and the battery has not been fully charged.

In this situation, solar power can fully support H_1. Extra power will first charge the battery before it can be provided to H_2.

Utility electric usage for H_1 and H_2,

$$U_{H1} = 0 \tag{11}$$
$$U_{H2} = max(H_{2m} - Ex, 0) \tag{12}$$
$$Ex = PV_m - H_{1m} - Batt_{ca} \tag{13}$$
$$Batt_{ca} = min(Batt_{max} - Batt, PV_m - H_{1m}) \tag{14}$$

Where
Ex: extra energy supply provided to H_2
$Batt_{ca}$ and $Batt_{max}$: battery charging amount and battery maximum capacity.
Hourly electric cost of H_1 and H_2

$$Cost_{H1} = 0 \tag{15}$$
$$Cost_{H2} = U_{H2}P_m + P_{NG}min(Ex, H_{2m}) \tag{16}$$

Electric Sale for H_1

$$S = P_{NG}min(Ex, H_{2m}) \tag{17}$$

C. Scenario 3: Solar power output is greater than H1 power consumption, and the battery has been fully charged.

In this situation, solar power can fully support H_1. All the extra power can be consumed by H_2. The remaining power gap for H_2 can be filled by the utility energy.
Utility electric usage for H_1 and H_2,

$$U_{H1} = 0 \tag{18}$$
$$U_{H2} = max(H_{2m} - (PV_m - H_{1m}), 0) \tag{19}$$

Hourly electric cost of H_1 and H_2

$$Cost_{H1} = 0 \tag{20}$$
$$Cost_{H2} = U_{H2}P_m + P_{NG}min(PV_m - H_{1m}, H_{2m}) \tag{21}$$

Electric Sale for H_1

$$S = P_{NG}min(PV_m - H_{1m}, H_{2m}) \tag{22}$$

D. Simulation Result

Setting the nanogrid price P_{NG} to be ¢10/kWh, Matlab simulation result of two households for August 12, 2019 are presented in Fig.9. They indicate that for H_1 the hourly utility energy consumption is approximately similar to consumption represented in Fig.7. For H_2, even with the augmentation from solar power, the price increase at 4 pm still exists due to significant reduction of solar irradiance after 3 pm. However, compared with Fig.2, the utility price spike happens at 3 pm, and price increase effect has been mitigated.

Table.I illustrates the total day cost for different situations.

1) If there is no Home PV System for both H_1 and H_2, the total costs of H_1 and H_2 are similar and higher than other situations.

TABLE I
TOTAL DAY COST

	H_1	H_2
Without PV	$46.06	$48.20
PV only for H_1	$5.54	$48.20
PV for nanogrid	$4.60	$29.50

2) When we use Home PV System for only H_1, there are substantial savings for H_1, while H_2 obviously remains the same.
3) For the nanogrid operating situation, the total cost of H_1 is consisted with the utility cost and the solar power sales to H_2. Therefore, the cost of H_1 is lower than the previous case.

Evidently, the operating strategy is better when the two households perform electric activities conjointly as a nanogrid. Both H_1 and H_2 can achieve considerable savings.

V. CONCLUSION

This paper discusses a case study of Home PV System operation strategy under the extreme weather condition. The north Texas area experienced an intensely high electricity consumption on August 12, 2019, which led to excessive utility price. Proposed study shows that, for residential customers with Home PV Systems, the utility cost surge can be effectively reduced. In addition, if these PV systems have interactions with another neighbor, the cost saving will be even more significant.

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