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Energy Storage-based Packetized Delivery of Electricity (ES-PDE)

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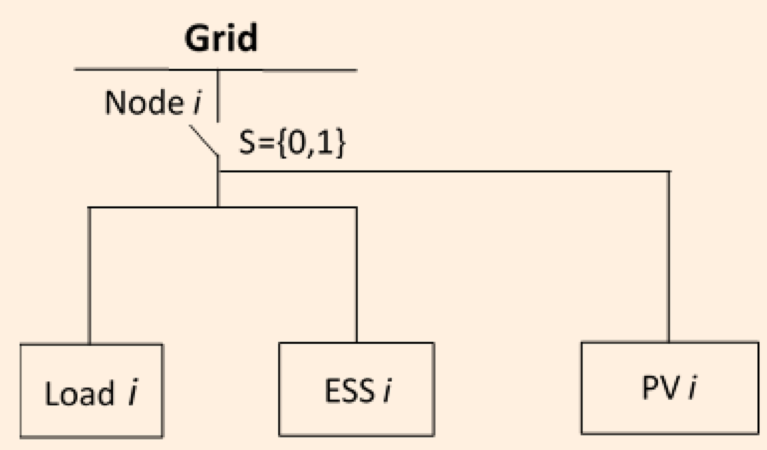
Abstract

This paper presents Energy Storage-based Packetized Delivery of Electricity (ES-PDE) under which loads are powered by energy storage systems (ESS) most of the time and only receive packets of electricity periodically to power themselves and to charge their ESSs. Main advantages of ES-PDE include: 1. Grid operators can schedule the delivery of electricity in a manner that utilizes existing grid infrastructure; 2. when grid outages occur, they can be self-powered for some time before the grid is fully restored.

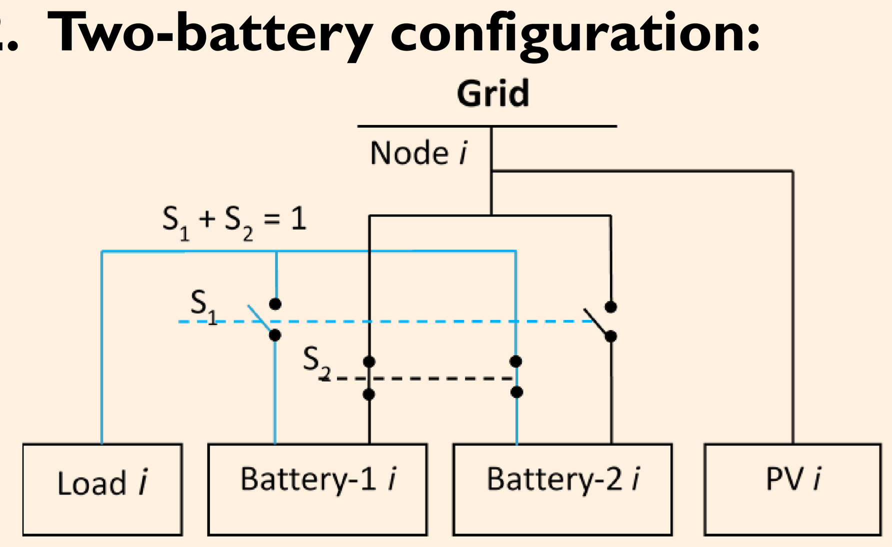
Electricity Packet Delivery Scheme

1. One-battery configuration:



- Grid-connected mode: S is closed.
- Standalone mode: S is open.

2. Two-battery configuration:



- Normal mode: S_1, S_2 are alternatively open and closed.
- Emergency mode: Both S_1 and S_2 are closed.

Optimization Formulation

Objective function:

$$\text{minimize: } P_{\max} = \max_h \left\{ \sum_i P_{\mathrm{g}}^{i,h} \right\}$$

Specific constraints for 1-bat configuration:

$$S^{i,h} = \eta_s S^{i,h-1} + \tau \left(\eta_c P_{\mathrm{c}}^{i,h} - P_{\mathrm{d}}^{i,h} \right)$$
$$0 \le S^{i,h} \le \overline{S^i},$$
$$S^{\mathrm{i,0}} = S^{\mathrm{i,H}}.$$
$$0 \le P_{\mathrm{c}}^{i,h} \le \alpha_{\mathrm{c}}^{i,h} \overline{P}^i$$
$$0 \le P_{\mathrm{d}}^{i,h} \le \alpha_{\mathrm{d}}^{i,h} \overline{P}^i$$
$$\alpha_{\mathrm{c}}^{i,h} + \alpha_{\mathrm{d}}^{i,h} \le 1.$$
$$P_{\mathrm{d}}^{i,h} - P_{\mathrm{c}}^{i,h} + P_{\mathrm{g}}^{i,h} + P_{\mathrm{pv}}^{i,h} \ge P_{\mathrm{l}}^{i,h}$$

Specific constraints for 2-bat configuration:

$$S^{i,h,x} = \eta_s S^{i,h-1,x} + \tau \left(\eta_c P_{\mathrm{c}}^{i,h,x} - P_{\mathrm{d}}^{i,h,x} \right)$$
$$0 \le S^{i,h,x} \le \overline{S^{i,x}},$$
$$S^{\mathrm{i,0,x}} = S^{\mathrm{i,H,x}}.$$
$$\sum_{x \in \{1,2\}} \left\{ P_{\mathrm{d}}^{i,h,x} \right\} \ge P_{\mathrm{l}}^{i,h},$$
$$\sum_{x \in \{1,2\}} \left\{ P_{\mathrm{c}}^{i,h,x} \right\} \le P_{\mathrm{g}}^{i,h} + P_{\mathrm{pv}}^{i,h}$$
$$0 \le P_{\mathrm{c}}^{i,h,x} \le \alpha_{\mathrm{c}}^{i,h,x} \overline{P}^i$$
$$0 \le P_{\mathrm{d}}^{i,h,x} \le \alpha_{\mathrm{d}}^{i,h,x} \overline{P}^i$$
$$\alpha_{\mathrm{c}}^{i,h,1} = \alpha_{\mathrm{d}}^{i,h,2},$$
$$\alpha_{\mathrm{d}}^{i,h,1} = \alpha_{\mathrm{c}}^{i,h,2},$$
$$\alpha_{\mathrm{c}}^{i,h,x} + \alpha_{\mathrm{d}}^{i,h,x} \le 1,$$

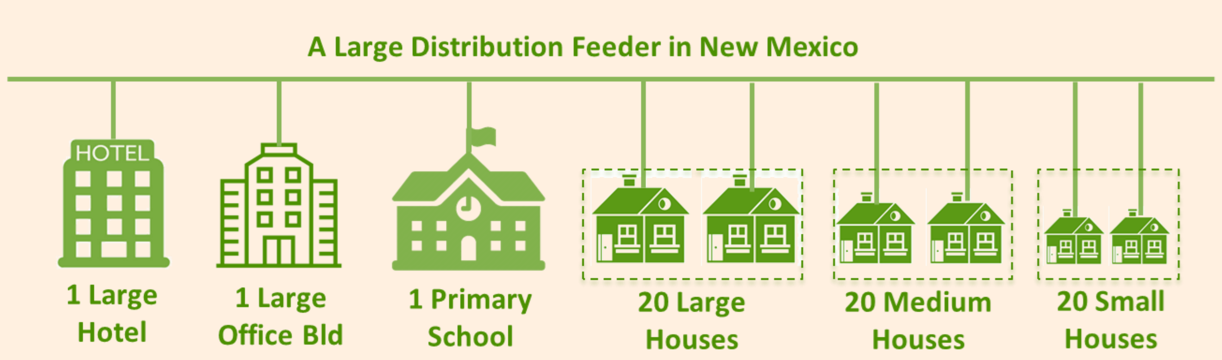
Linearization constraint: $\sum_i P_{\mathrm{g}}^{i,h} \le P_{\max}, \ \forall h$

Constants	Description	Unit
τ	Time step duration	hour
h	Time step index	-
i	Node index	-
x	ESS index $\in \{1,2\}$	-
H	Time horizon	-
$\overline{S}^{i,x}$	Energy capacity of ESS-x at i	kWh
$\overline{P}^{i,x}$	ESS's power rating of ESS-x at i	kW
η_s	ESS's self-discharge efficiency $\in [0,1]$	-
η_c	ESS's round-trip efficiency $\in [0,1]$	-
$P_{\mathrm{l}}^{i,h}$	Load forecast at i during h	kW
$P_{\mathrm{pv}}^{i,h}$	PV forecast at i during h	kW

Variables	Description	Unit
$P_{\max}$	Peak load of the feeder over time horizon H	kW
$P_{\mathrm{g}}^{i,h}$	Grid power at i during h	kW
$P_{\mathrm{c}}^{i,h,x}$	Charge power of ESS-x at i during h	kW
$P_{\mathrm{d}}^{i,h,x}$	Discharge power of ESS-x at i during h	kW
$\alpha_{\mathrm{c}}^{i,h,x}$	Binary charge status of ESS-x at i during h	-
$\alpha_{\mathrm{d}}^{i,h,x}$	Binary discharge status of ESS-x at i during h	-
$S^{i,h,x}$	The state of energy of ESS-x at i during h	kWh

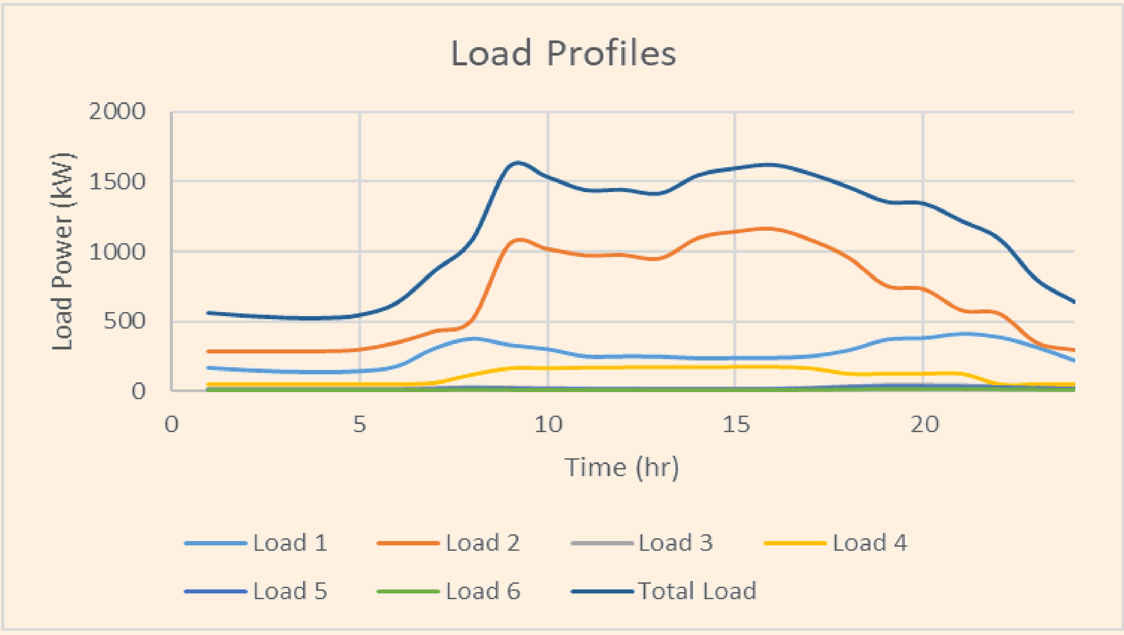
Case Studies

A hypothetical utility feeder is considered.

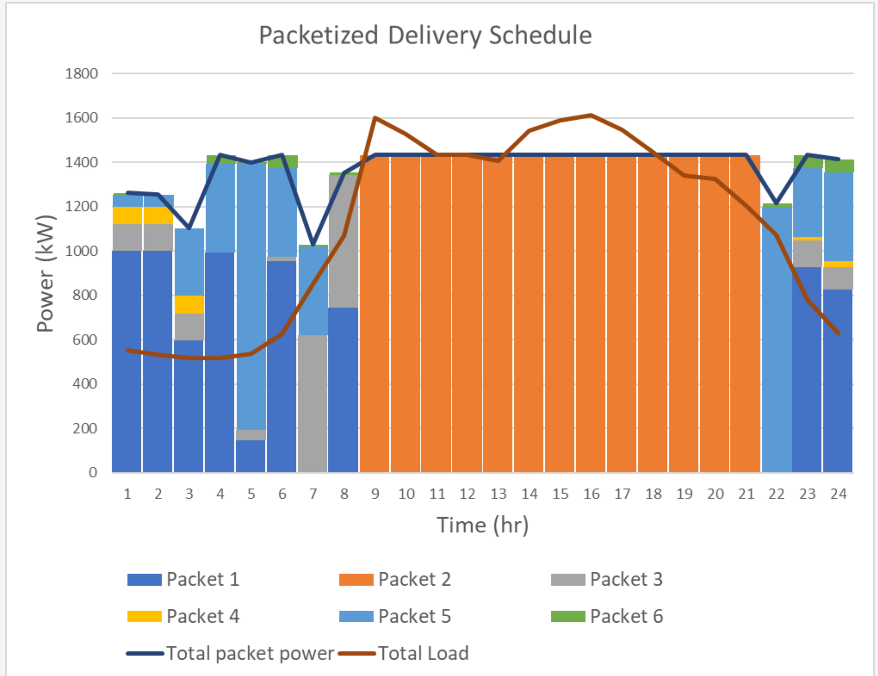


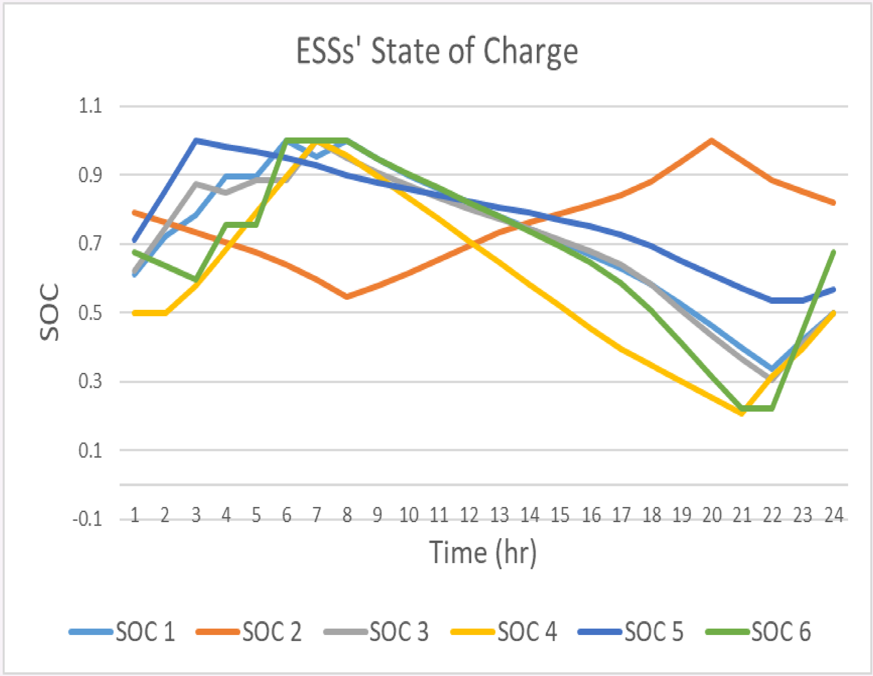
Assumptions:

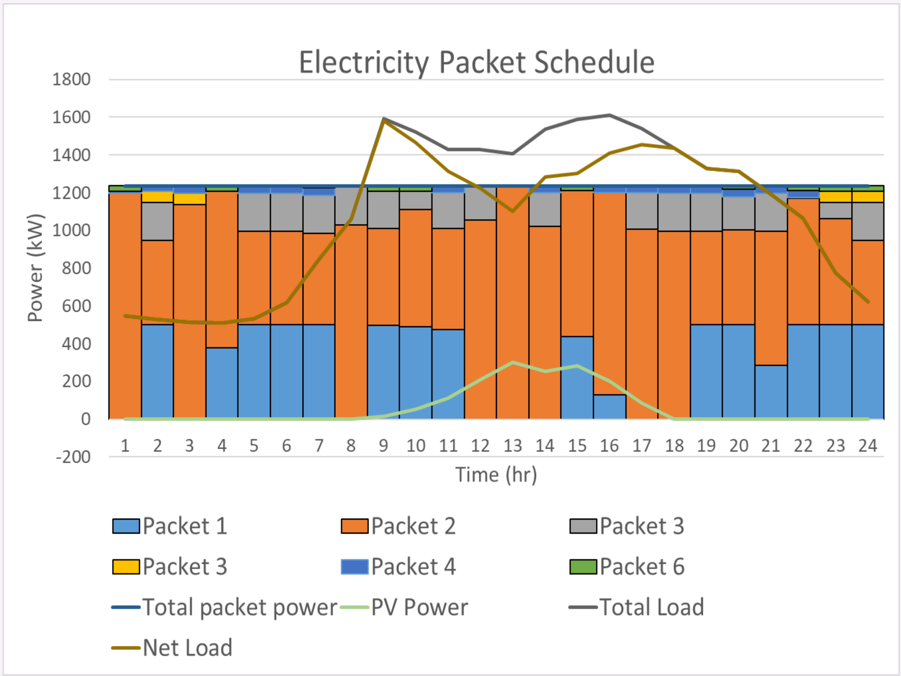
- Residential loads are clustered together in three groups.
- Batteries are associated with each load or load cluster.
- The size of the batteries are selected so that they can power the associated loads the whole day.
- The operator wants to minimize the peak load of the feeder.

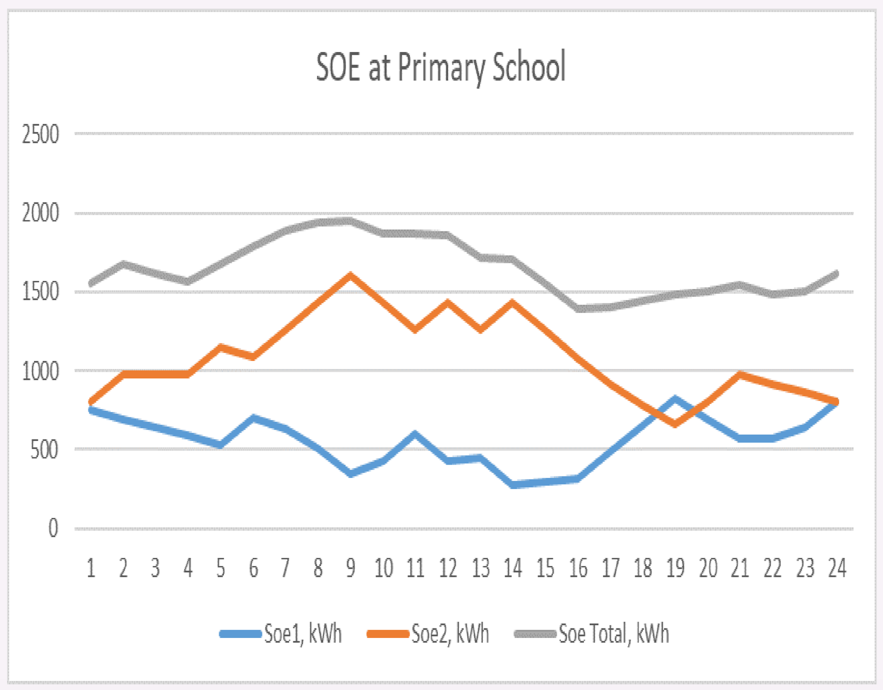


Case Studies – Results









1-battery configuration

2-battery configuration

Conclusions

In this paper, the packetized energy concept has been realized using ESSs. Two configurations including one-battery and two-battery configurations are proposed for the delivery of energy packets to the customers. While the one-battery configuration is easier and more economical for realization, the two-battery configuration can fully decouple the load and the utility grid by adding another battery.

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