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Performance, Costs, and GHG Emissions of PV-Hybrid Systems: Current Status and Avenues for Improvement

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Objectives

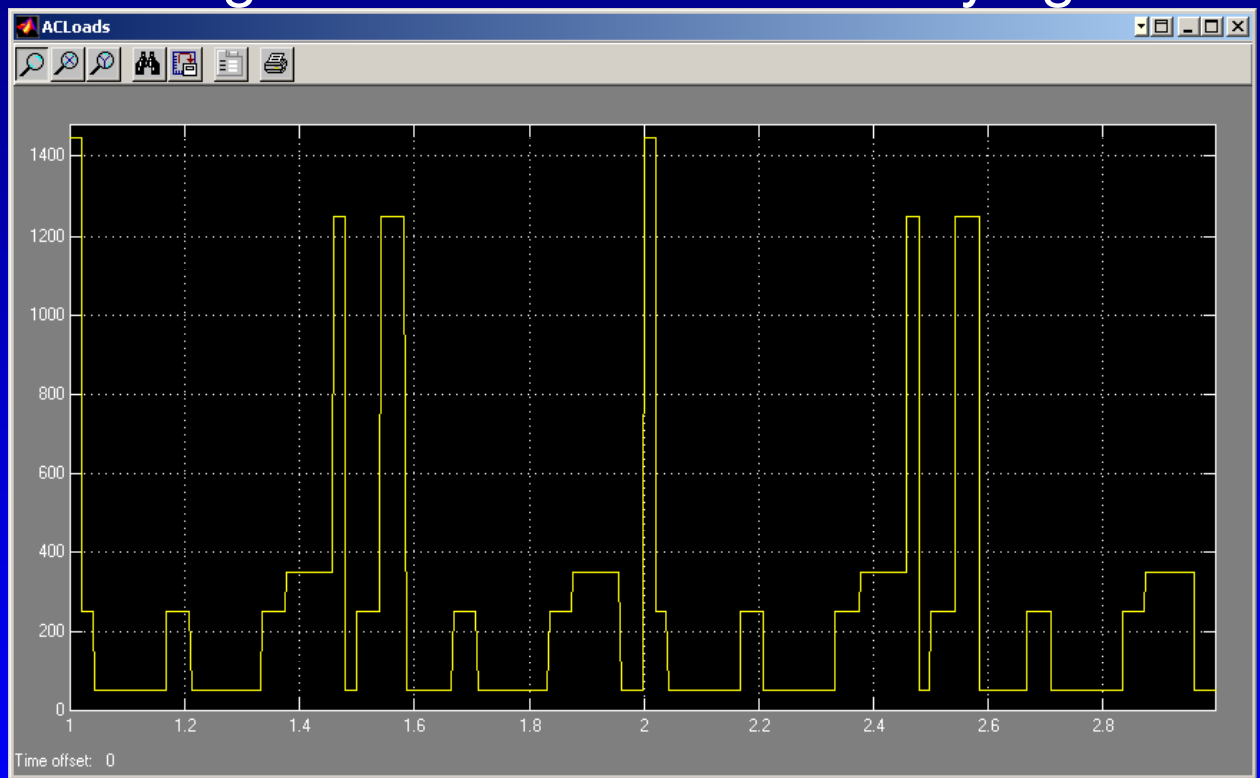
- Determine the overall costs and GHG emissions of PV hybrid systems built according to current standard practices
- Compare these costs and GHG emissions to those of competing power sources, including PV-battery, prime power, and genset-battery systems
- Investigate how much PV hybrid system costs and emissions could be reduced by various avenues of improvement

Method

- Simulation with PVToolbox in Matlab/Simulink
  - Energy flows accurate to within 5 to 8%
  - Assume errors in System A will be matched by errors in System B, such that differences of ~2% are significant
  - Component lifetime estimates much more rudimentary
- CWEEDs meteorological data for 5 year period and 5 cities across Canada
- Total of 47 different combinations of system configuration, load, location (too much data!)

Simulation Details

- 303 W average load: 50 W DC and varying AC load



- Toronto weather
  - Fuel consumption and battery deterioration at different locations comparable when solar fraction set to 65%

Prime Power System

- 5 kW diesel genset operating year round
  - Smaller diesel gensets rare
- Rectifier with 92.5% efficiency at 50 W (DC load)

Genset-battery System

- 5 kW diesel
- 5 kW rectifier
- 24 V, 24 kWh battery
  - Genset turned on at 40% state-of-charge, yielding 2 days autonomy
  - Genset turned off after 2 hours of constant voltage charging at 28.5 V
- 1.5 kW inverter

PV Hybrid System

- Genset-battery system plus 1.65 kWp array
  - Facing due south, tilted at 45º
  - Ideal (lossless) maximum power point tracker

PV-battery System

- Array/battery combination achieved 1% loss-of-load probability (load unmet 3.7 days of the year)
  - 6.5 kWp array tilted at 60º to horizontal
  - 40.8 kWh battery that would discharge to 80% depth-of-discharge
- No genset or rectifier

Genset and Battery Component Models

- 5 kW AC genset
  - 0.6 l/kWh, or 3 l/h at 100% load,
  - 0.75 l/h at 0% load
  - Fuel consumption varies linearly in between full and no load
  - Nominal lifetime of 10,000 h
  - At 50 to 100% loading, wear at rate of 1 overhaul every 5000 h
  - Below 50% loading, wear rate increases linearly to 1 overhaul every 2500 h of no load operation
- Battery
  - Current/voltage/SOC behaviour modelled on GNB Absolyte
  - Held at 25º C
  - 800 cycles at 80% DOD and 1500 cycles at 50% DOD
  - Calendar lifetime of 12 years

Simulated System Performance

	Prime Power	Genset-Battery	PV-Battery	PV Hybrid
Genset Fuel Consumption	7769 l	2245 l	NA	781 l
Genset Run Time	8760 h	884 h	NA	314 h
Genset Overhauls	3.29	0.19	NA	0.07
Genset Starts	1	212	NA	76
Genset Efficiency	3%	11%	NA	11%
Battery Capacity Deterioration	NA	1933 Wh	446/3400 Wh	1189 Wh
Fraction Solar	NA	NA	98.9%	64.6%
Fraction of Solar Energy Wasted	NA	NA	59.1%	3.7%
Fraction of Wasted Energy that can be Avoided with Nonseasonal Storage	NA	NA	0.8%	99.5%

Cost Assumptions for Remote Industrial Site

- 10% discount rate, no inflation, project life of 25 years
- Fuel cost $2.00 per l delivered
- Genset: $5000 purchase, $2000 overhaul, + $1.00 / h for other maint.
- Battery cost $400 per kWh of capacity
- PV $8 / Wp, inverter $1 / W, and rectifier $0.30 / W
- Component lifetimes (years):

	Prime Power	Genset-Battery	PV-Battery	PV Hybrid
PV Array	NA	NA	25	25
Battery	NA	4.1	12	6.7
Genset (overhauled once)	0.61	10.6	NA	29.0
Inverter	NA	12.5	12.5	12.5
Rectifier	12.5	12.5	12.5	12.5

Costs at Remote Industrial Site

	Prime Power	Genset-Battery	PV-Battery	PV Hybrid
Genset Fuel	$15,538	$4,490		$1,562
Genset Purchase	$8,882	$787		$534
Genset Overhaul	$3,451	$190		$54
Genset Maintenance	$8,760	$884		$314
Battery Purchase		$2,968	$2,395	$2,034
PV Purchase			$5,729	$1,454
Inverter Purchase		$215	$215	$215
Rectifier Purchase	$13	$215		$215
Total Annual Cost	$36,644	$9,749	$8,339	$6,382
Initial System Costs	$5,090	$17,600	$69,820	$25,800
Cost of Electricity	$13.81/kWh	$3.67/kWh	$3.14/kWh	$2.40/kWh

(annual costs except for “Initial System Costs” line)

- Even if genset were free, cost of electricity for hybrid system would fall by only 14%

Costs at Residential Site

	Prime Power	Genset-Battery	PV-Battery	PV Hybrid
Genset Fuel	$1,593	$2,245		$781
Genset Purchase	$9,254	$1,041		$414
Genset Overhaul				
Genset Maintenance	$876	$88		$31
Battery Purchase		$2,264	$1,874	$1,514
PV Purchase			$5,013	$1,272
Inverter Purchase		$215	$215	$215
Rectifier Purchase	$13	$215		$215
Total Annual Cost	$11,736	$6,069	$7,102	$4,442
Initial System Costs	$1,090	$8,800	$55,160	$20,350
Cost of Electricity	$4.42/kWh	$2.29/kWh	$2.68/kWh	$1.67/kWh

(annual costs except for “Initial System Costs” line)

Embodied Energy, Industrial Site

	Prime Power	Genset-Battery	PV-Battery	PV Hybrid
Mono-Si PV Array	0	0	10,700 MJ	2,700 MJ
Diesel Genset	15,200 MJ	880 MJ	0	320 MJ
Lead-Acid Batteries	0	6,260 MJ	3,640 MJ	3,830 MJ
System Energy Content	15,200 MJ	7,140 MJ	14,340 MJ	6,850 MJ
Fuel Energy Content	303,000 MJ	87,600 MJ	0	30,500 MJ

- Electricity consumed in manufacture converted to primary energy equivalent
- All figures given on annual basis

GHG emissions, Industrial Site

	Prime Power	Genset-Battery	PV-Battery	PV Hybrid
Mono-Si PV Array	0	0	0.59	0.15
Diesel Genset	0.80	0.05	0	0.02
Lead-Acid Batteries	0	0.35	0.20	0.21
Annual Equipment GHG Emissions	0.80	0.40	0.79	0.38
Annual GHG Emissions from Fuel	21	6.1	0	2.1
Total Annual GHG Emissions	21.8	6.5	0.79	2.5
Emissions per unit of Electricity	8.2 tCO_2/MWh	2.4 tCO_2/MWh	0.3 tCO_2/MWh	0.9 tCO_2/MWh

- All figures given on annual basis
- Emissions for grid electricity in Canada: 0.211 tCO_2/MWh

Avenues for Hybrid System Improvement

	Fuel + Maintenance Costs	Cost of electricity	GHG emissions
Baseline	$0.72/kWh	$2.40/kWh	0.9 t CO2
2.5 kW rectifier	+23%	+6%	+11%
No cost, maintenance-free genset	-21%	-14%	
50% longer battery lifetime		-8%	-3%
45% larger array	-41%	-7%	-33%
Eliminating absorb charging (part load)	-18%	-3%	-11%
Minimizing wasted solar energy	-25%	-5%	-18%

- Possible reductions in cost of electricity ~20%
- Possible reductions in GHG emissions > 50%

Conclusions

- Providing small quantities of reliable power off grid is very expensive: $1.50 to $4.00 per kWh
  - PV hybrid systems are most cost-effective option for small to moderate loads
- GHG emissions for all off-grid power systems examined here exceed average grid emissions for Canada
- Changes in design and control may reduce total cost of electricity for hybrid system by up to 20%
- But GHG emissions from hybrid system may be reduced by over 50% while reducing cost of electricity!

Questions?