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A Simple, Rigorous Method for Sizing the Array of a PV Hybrid System

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The Problem

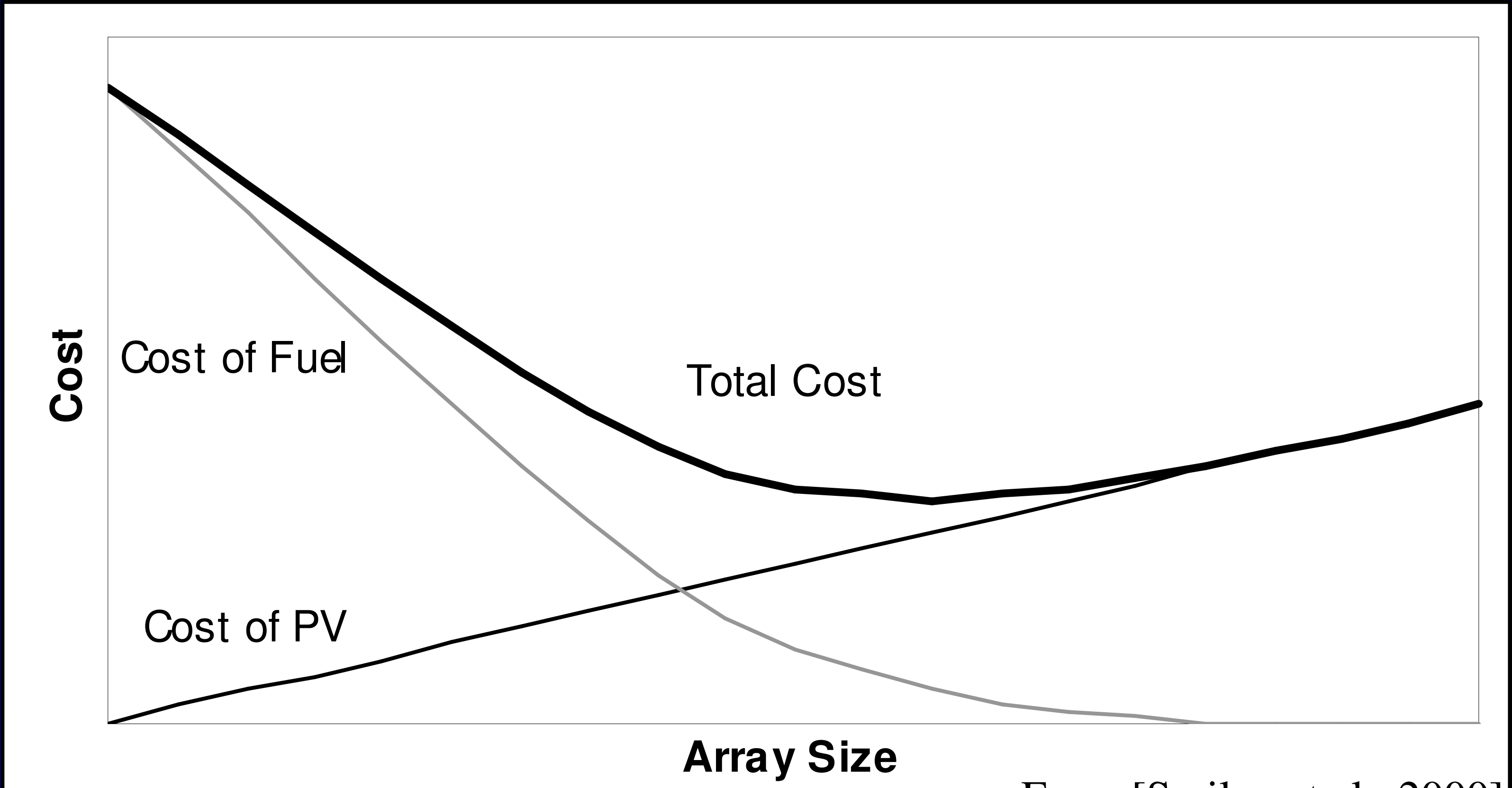
What is the optimum size for the array of a PV hybrid system?

Typical Solutions

- Rules of thumb
  - e.g., “Size the array to meet 60% of the load on an annual basis”
  - But this ignores the financial aspects of optimization
- Simulation and sizing software
  - Hides the optimization problem, so user may have difficulty interpreting results and catching errors
  - Software programs are not gods
- But a simple, rigorous approach exists!

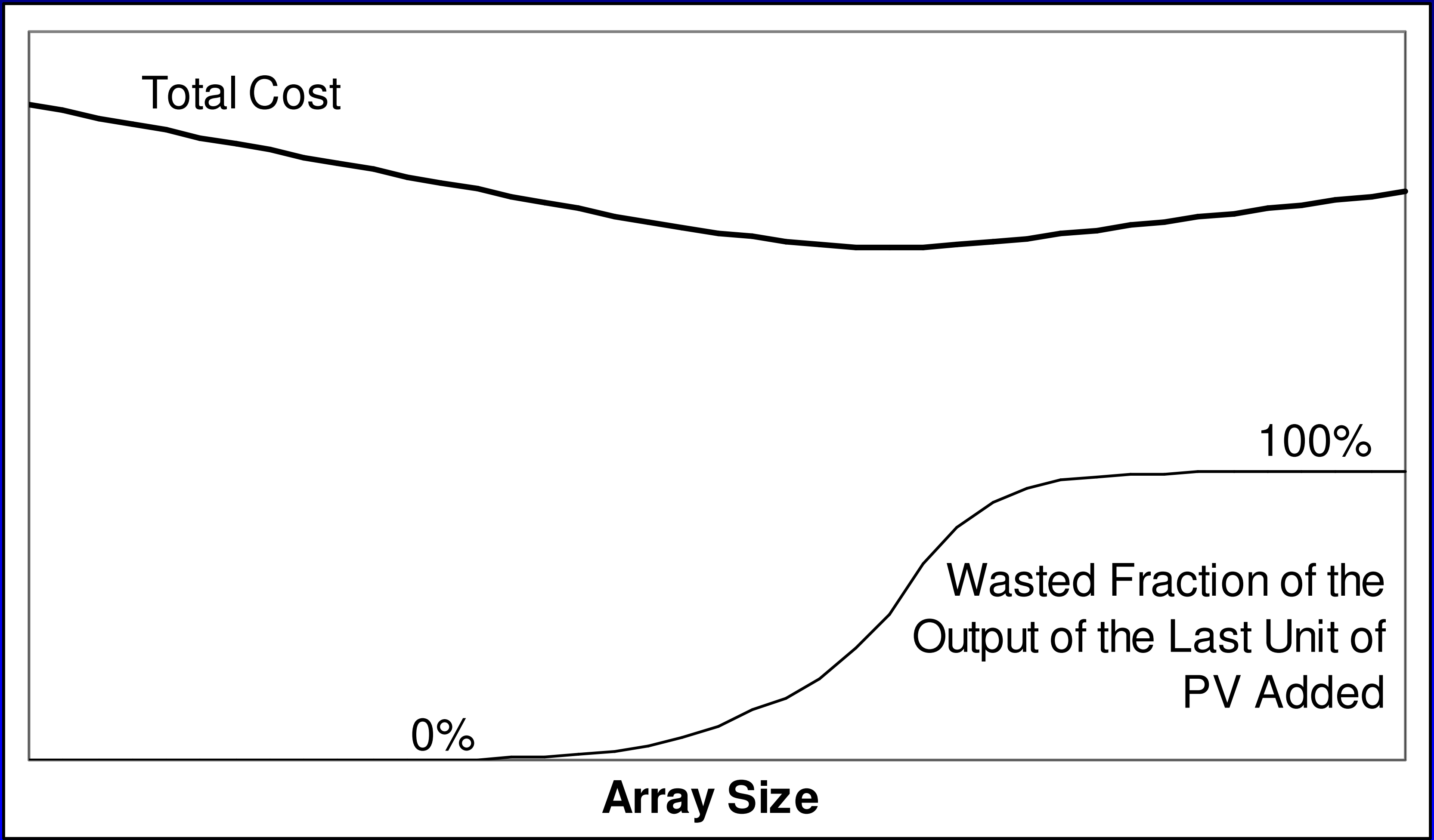
The Nature of the Optimization Problem

- Significant costs: array purchase and genset operation

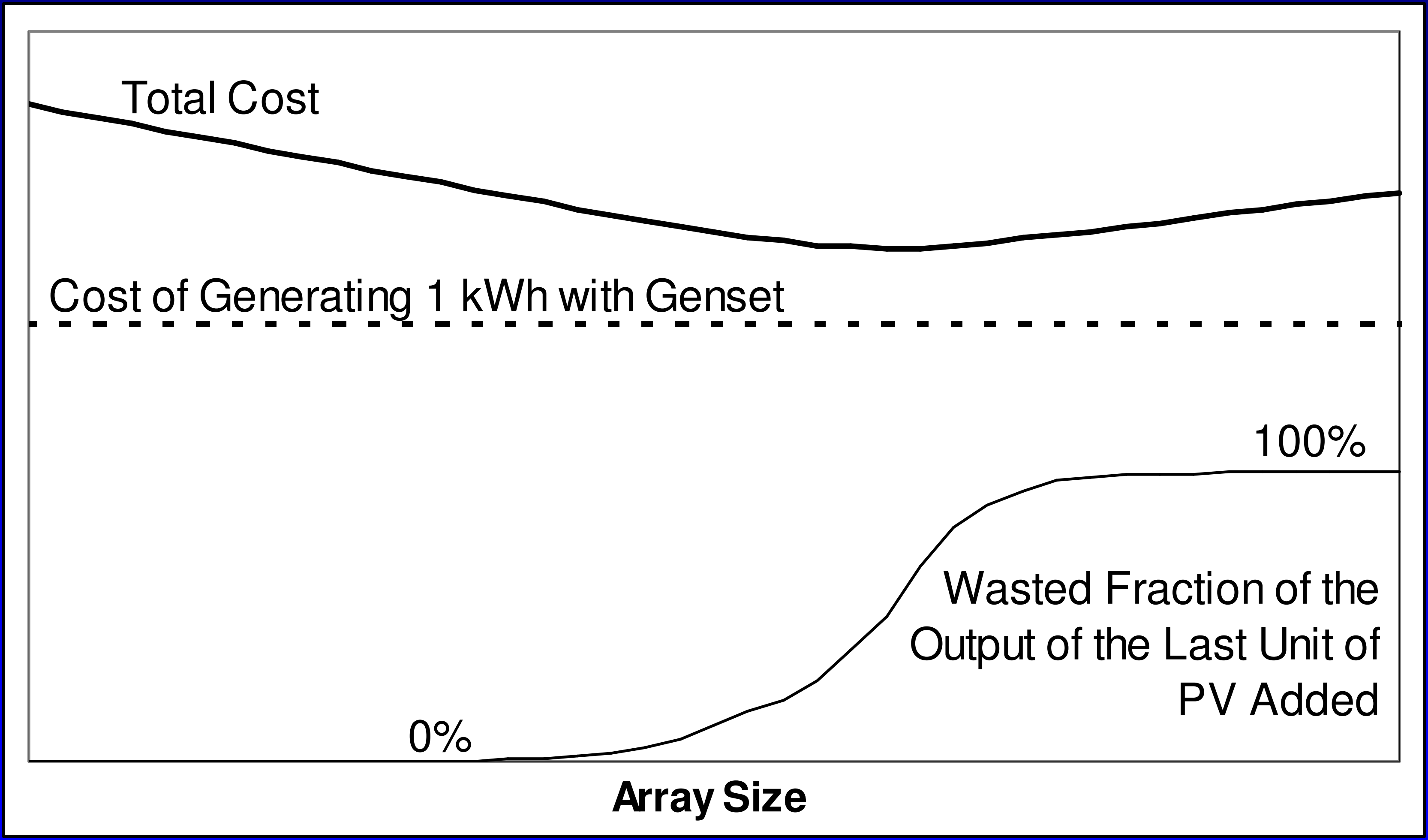


From [Smiley et al., 2000]

Waste and the Last Unit of PV Added



Waste and the Last Unit of PV Added



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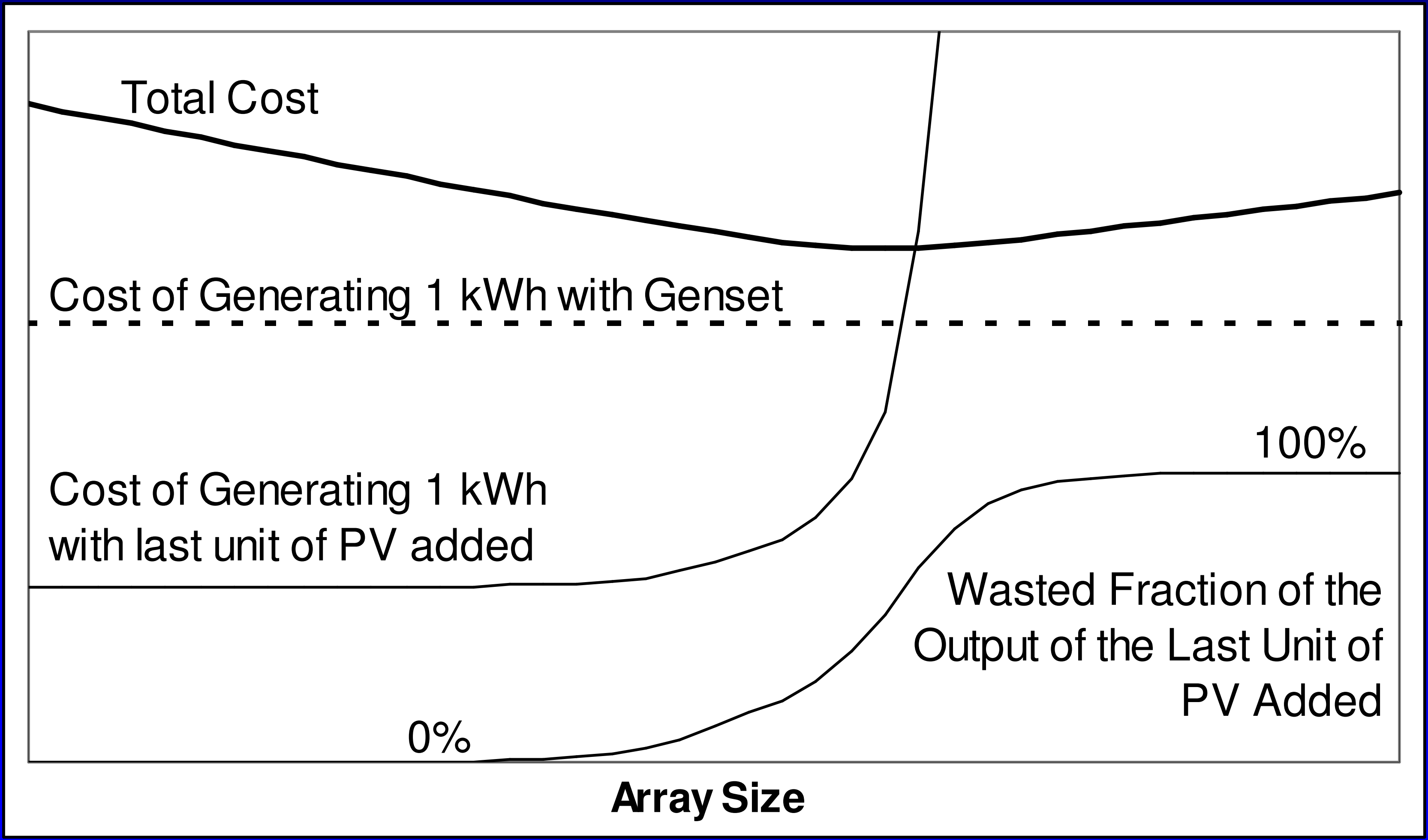

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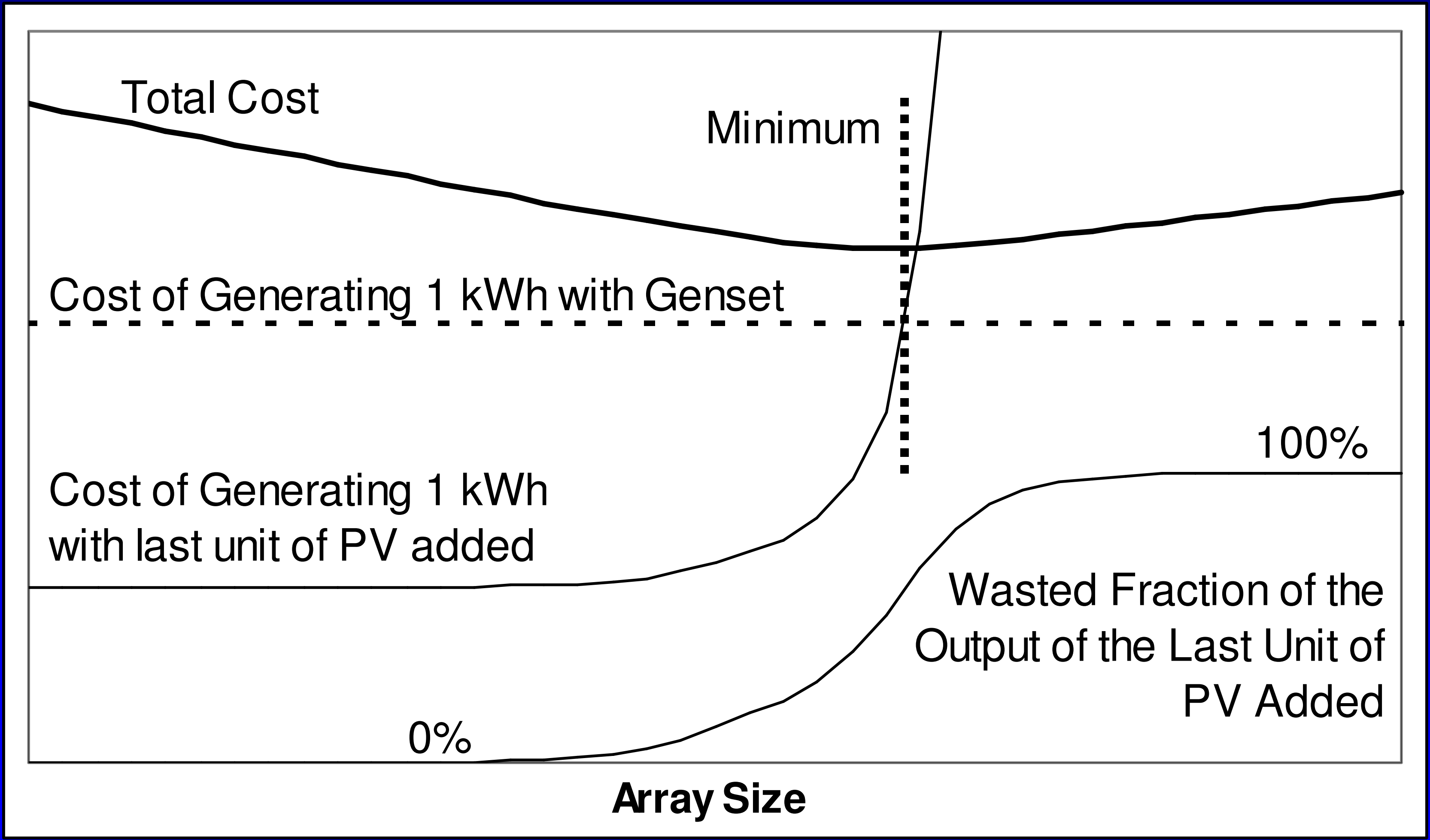

At the minimum total cost…

Cost of generating 1 kWh with genset = Cost of generating 1 kWh with last unit of PV added

$$C_{genset} = \frac{C_{PV}}{\left(1 - f_{PVWaste}\right)}$$

Rearranging…

$$f_{PVWaste} = 1 - \frac{C_{PV}}{C_{genset}}$$

Optimization Method

1. Calculate C_{PV}, the cost of generating 1 kWh of electricity with PV, assuming none of it is rejected by the charge controller
2. Calculate C_{genset}, the cost of generating 1 kWh of electricity with the genset
3. Add PV until, for the last unit of PV added, the fraction of its output that is wasted is:

$$f_{PVWaste} = 1 - \frac{C_{PV}}{C_{genset}}$$

Calculating C_{PV}: Example for Winnipeg

$$C_{PV} = \frac{c_{array\ capacity}}{E_{array}}$$

$C_{array\ capacity} \approx \$8 / W_p$ installed

Available solar energy in plane of array ≈ 1670 kWh/m^2/year

Output of ideal 1 W_p array ≈ 1.67 kWh/year

- After 3 % losses for dust, snow, rain: 1.62 kWh/year
- After 5 % losses in MPPT charge controller: 1.54 kWh/year
- After 3% wiring losses: 1.49 kWh/year
- After losses in battery and inverter: 1.32 kWh/year

E_{array} = 20 years · 1.32 kWh/year = 26.4 kWh per W_p

C_{PV} = 8 / 26.4 = \$0.30 / kWh

Calculating C_{genset}: Example for Winnipeg

$$C_{genset} = \frac{PV\left(r_{fuel}, n, c_{fuel}\right) + PV\left(r_{maintenance}, n, c_{maintenance}\right)}{n}$$

Specific fuel consumption = 0.67 litres/kWh at 60% loading factor

After charger and battery inefficiencies: 0.83 litres/kWh

If delivered cost of fuel is $1.20, then c_{fuel} is $0.99/kWh

For 10 kVA genset at 60% loading, after inefficiencies: 0.2 h/ kWh

Maintenance of $1 per hour of operation

Overhaul costs of $2000 per 10,000 hours of operation

Then $c_{maintenance}$ is $1.20/h · 0.2 h/kWh = $0.25/kWh

Assume discount rate of 10%, inflation of 2%, fuel cost escalation of 3%

Then $r_{fuel} \approx 10 - 3 = 7\%$ and $r_{maintenance} \approx 10 - 2 = 8\%$

For $n = 20$ year project, C_{genset} = $0.65/kWh

Applying the Method: Example for Winnipeg

$$f_{PVWaste} = 1 - \frac{C_{PV}}{C_{genset}}$$

$$= 1 - \frac{\$0.30}{\$0.65}$$

$$= 54\%$$

- Want to add PV until 54% of output last unit is wasted
- Do we need simulation to determine waste?
- No: can use pen, paper, and a table of values
- Consider Winnipeg example with 4.8 kWh/day load

Determining the wasted fraction of the output from the last unit of PV added

- Assume:
  - At a critical array size for a given month, the array will exactly meet the requirements of the load and associated losses
  - At smaller array sizes, none the array's output is rejected
  - All output from that part of the array larger than the critical size is rejected
- So in a given month, the wasted fraction of the output of the last unit of PV added is 0% if the array is subcritical and 100% if the array is supercritical
  - In reality, the charge controller rejects energy at subcritical array sizes and makes use of energy at super critical array sizes
  - But when all months are considered together, these errors average out

Winnipeg Example

	Average Daily Solar Radiation in Plane of Arr. (kWh/m²/day)	Fraction of annual solar radiation	Fraction of annual output wasted by last unit of PV	Critical Array Size (W_p)	
January	3.59				
February	4.83				
March	5.66				
April	5.45				
May	5.39				
June	5.39				
July	5.69				
August	5.38				
September	4.42				
October	3.46				
November	2.81				
December	2.78				

Winnipeg Example

	Average Daily Solar Radiation in Plane of Arr. (kWh/m^2/day)	Fraction of annual solar radiation	Fraction of annual output wasted by last unit of PV	Critical Array Size (W_p)	
January	3.59			1692	
February	4.83			1257	
March	5.66			1074	
April	5.45			1114	
May	5.39			1126	
June	5.39			1128	
July	5.69			1067	
August	5.38			**1129**	
September	4.42			1375	
October	3.46			1754	
November	2.81			2163	
December	2.78			2186	

Winnipeg Example

	Average Daily Solar Radiation in Plane of Arr. ($kWh/m^2/day$)	Fraction of annual solar radiation	Fraction of annual output wasted by last unit of PV	Critical Array Size (W_p)	
January	3.59	6.55%		1692	
February	4.83	8.81%		1257	
March	5.66	10.31%		1074	
April	5.45	9.94%		1114	
May	5.39	9.84%		1126	
June	5.39	9.82%		1128	
July	5.69	10.38%		1067	
August	5.38	9.81%		**1129**	
September	4.42	8.05%		1375	
October	3.46	6.31%		1754	
November	2.81	5.12%		2163	
December	2.78	5.06%		2186	

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July	5.69	10.38%	10.38%	1067	
August	5.38	9.81%		**1129**	
September	4.42	8.05%		1375	
October	3.46	6.31%		1754	
November	2.81	5.12%		2163	
December	2.78	5.06%		2186	
	Total fraction of annual output wasted by last unit of PV		10.38%		

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August	5.38	9.81%		**1129**
September	4.42	8.05%		1375
October	3.46	6.31%		1754
November	2.81	5.12%		2163
December	2.78	5.06%		2186
	Total fraction of annual output wasted by last unit of PV		20.69%	

Winnipeg Example

	Average Daily Solar Radiation in Plane of Arr. (kWh/m²/day)	Fraction of annual solar radiation	Fraction of annual output wasted by last unit of PV	Critical Array Size (W_p)
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July	5.69	10.38%	10.38%	1067
August	5.38	9.81%		**1129**
September	4.42	8.05%		1375
October	3.46	6.31%		1754
November	2.81	5.12%		2163
December	2.78	5.06%		2186
	Total fraction of annual output wasted by last unit of PV		30.63%	

Winnipeg Example

	Average Daily Solar Radiation in Plane of Arr. (kWh/m²/day)	Fraction of annual solar radiation	Fraction of annual output wasted by last unit of PV	Critical Array Size (W_p)	
January	3.59	6.55%		1692	
February	4.83	8.81%		1257	
March	5.66	10.31%	10.31%	1074	
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June	5.39	9.82%		1128	
July	5.69	10.38%	10.38%	1067	
August	5.38	9.81%		**1129**	
September	4.42	8.05%		1375	
October	3.46	6.31%		1754	
November	2.81	5.12%		2163	
December	2.78	5.06%		2186	
	Total fraction of annual output wasted by last unit of PV		40.47%		

Winnipeg Example

	Average Daily Solar Radiation in Plane of Arr. (kWh/m²/day)	Fraction of annual solar radiation	Fraction of annual output wasted by last unit of PV	Critical Array Size (W_p)	
January	3.59	6.55%		1692	
February	4.83	8.81%		1257	
March	5.66	10.31%	10.31%	1074	
April	5.45	9.94%	9.94%	1114	
May	5.39	9.84%	9.84%	1126	
June	5.39	9.82%	9.82%	1128	
July	5.69	10.38%	10.38%	1067	
August	5.38	9.81%		**1129**	Optimal
September	4.42	8.05%		1375	
October	3.46	6.31%		1754	
November	2.81	5.12%		2163	
December	2.78	5.06%		2186	
	Total fraction of annual output wasted by last unit of PV		50.29%		

Example with different load each month

	Average Daily Solar Radiation in Plane of Arr. ($kWh/m^2/day$)	Average daily load (kWh/day)	Critical Array Size (W_p)	Rank in terms of critical array size (1=smallest)	Fraction of annual solar radiation	Fraction of annual output wasted by last unit of PV	
January	3.59	3.0	1057	5	6.55%	6.55%	
February	4.83	4.3	**1126**	6	8.81%	8.81%	
March	5.66	4.7	1051	4	10.31%	10.31%	
April	5.45	5.5	1276	10	9.94%		Optimal size
May	5.39	5.2	1220	8	9.84%		between size
June	5.39	4.3	1010	3	9.82%	9.82%	for February
July	5.69	5.5	1222	9	10.38%		and September
August	5.38	4.0	941	2	9.81%	9.81%	
September	4.42	4.0	**1146**	7	8.05%		
October	3.46	4.8	1754	11	6.31%		
November	2.81	4.7	2118	12	5.12%		
December	2.78	2.0	911	1	5.06%	5.06%	
				Total fraction of annual output wasted by last unit of PV		50.36%	

Interpretation

- If $C_{genset} / C_{PV} < 1$ then hybrid system does not make sense
- If C_{genset} / C_{PV} is near unity, then oversized array costly
- If C_{genset} / C_{PV} is large, then undersized array costly

- If monthly critical array sizes are evenly scattered over a large range, then genset operating costs fall off gradually, and an oversized array is generally okay
  - This is not the case for more equatorial sites or where the average load is strongly correlated with the availability of sunshine

- If the desired $f_{PVWaste}$ is nearly unity, then a PV-battery system may make sense

Refinements

- Battery wear can be included in C_{genset} and C_{PV}
  - Generally unnecessary
- Partial state-of-charge cycling shortens battery lifetime
  - Full charging with the genset is expensive
  - A larger PV array increases likelihood of regular full charging
  - Where C_{genset} / C_{PV} is large, increase size of array by 10 to 25% beyond sizing suggested by $f_{PVWaste}$

Why bother?

- For Winnipeg example examined here, one popular software tool suggested an array of 550 W_p!
- Increasing array size from 550 to 1130 W_p decreased the total present value of array and future genset operating costs by over $5000, as estimated by the software package itself

Questions?