Material Handling Fuel Cells for Building Electric Peak Shaving Applications

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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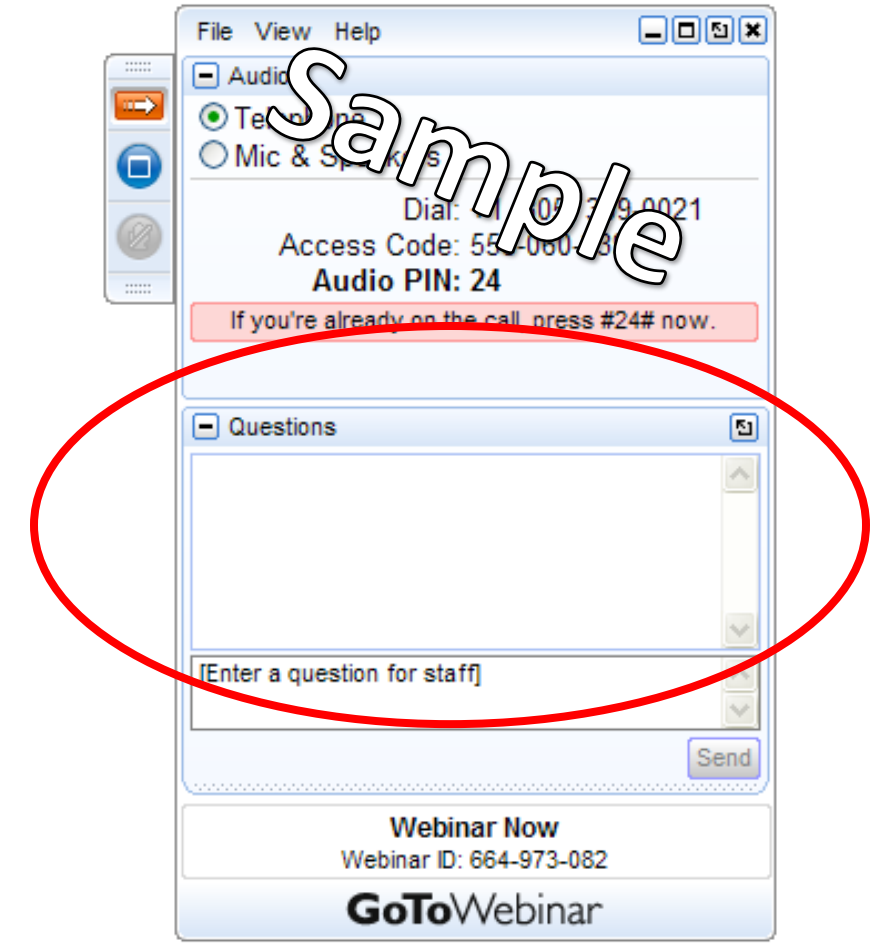
U.S. Department of Energy
Fuel Cell Technologies Office
August 11, 2015

Question and Answer

- Please type your question into the question box



hydrogenandfuelcells.energy.gov

Acknowledgments

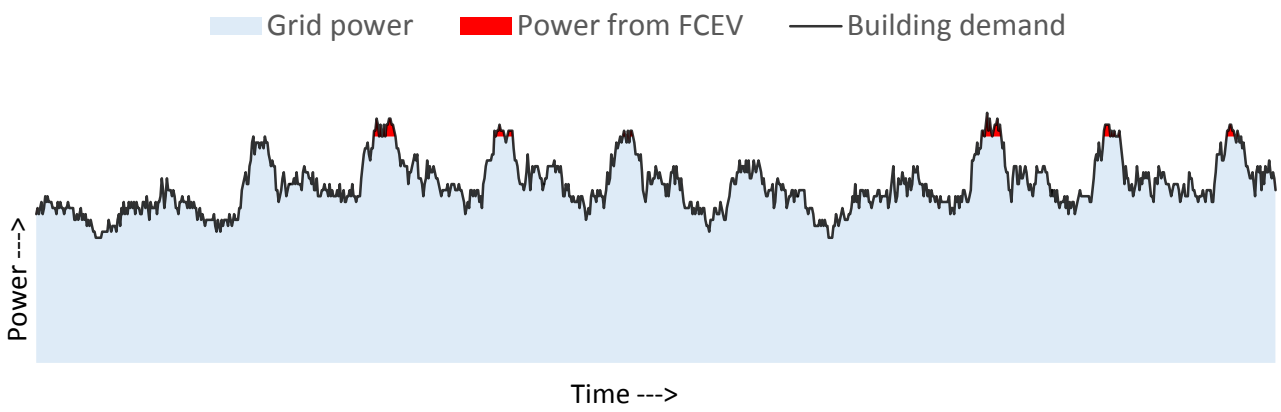
Fuel Cell Technologies Office, DOE EERE

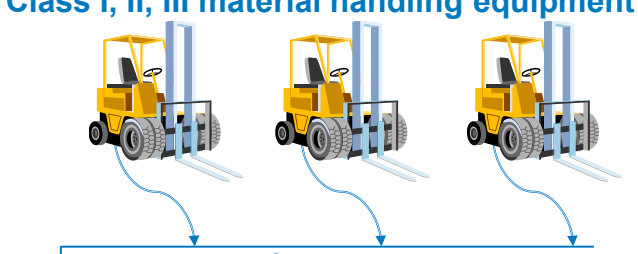
For providing funding for this project and for supporting sustainable hydrogen technology development through analysis, demonstration, and market transfer.

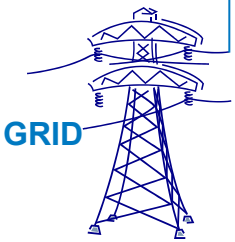
Pete Devlin, Market Transformation and Interagency Coordination Manager

For embracing new technology application ideas and diligently guiding them from analysis to demonstration. For always seeking partnership opportunities to yield product demonstrations and smooth market adoption.

H_2 Material Handling Application Concept



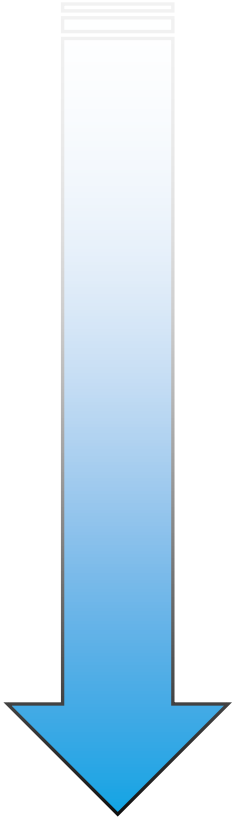




Forklift power packs can provide value-added by reducing building peak electric demand.

Value of Peak Power (PG&E)

Smaller customers



Larger customers

Rate Schedule	Customer Charge	Season	Time-of-Use Period	Demand Charge (per kW)			Time-of-Use Period	Total Energy Charge (per kWh)		
A-1	Single Phase Service per meter/day =$0.32854 Polyphase Service per meter/day =$0.65708	**Summer**		-				$0.21446		
		Winter		-				$0.15102		
A-1 TOU	Single Phase Service per meter/day =$0.32854 Polyphase Service per meter/day	**Summer**		-			On peak	$0.23200		
							Part Peak	$0.22438		
							Off Peak	$0.20121		
A-6 TOU	day for A6 or A6X; =$0.05914 per day for A6W[5/]	**Winter**		-			Part Peak	$0.15915		
							Off Peak	$0.13163		
				Secondary	**Primary**	**Transmission**		**Secondary**	**Primary**	**Transmission**
A-10 (Table A)	$4.59959 per meter per day	**Summer**		$13.49	$12.67	$8.71		$0.14513	$0.13531	$0.11058
		Winter		$6.41	$6.62	$4.88		$0.10699	$0.10205	$0.08915
A-10 TOU (Table B)	$4.59959 per meter per day	**Summer**		$13.49	$12.67	$8.71	Peak	$0.15999	$0.14771	$0.12186
							Part-Peak	$0.15326	$0.14291	$0.11747
							Off-Peak	$0.13280	$0.12457	$0.10082
		Winter		$6.41	$6.62	$4.88	Part-Peak	$0.11600	$0.10940	$0.09593
							Off-Peak	$0.09845	$0.09505	$0.08272
E-19 TOU	Meter charge: =$4.77700/day for E19 V or X; =$4.63507/day for E19W[4/]; =$19.71253/day for E19S mandatory; =$32.85421/day for E19P mandatory; =$59.13758/day for E19T mandatory	**Summer**	Max. Peak	$16.27	$16.09	$14.19	Peak	$0.14453	$0.13284	$0.08481
			Part Peak	$3.78	$3.47	$3.14	Part Peak	$0.09985	$0.09407	$0.08094
			Maximum	$12.78	$10.10	$6.17	Off Peak	$0.07059	$0.07098	$0.06743
		Winter	Part Peak	$0.22	$0.41	$0.00	Part Peak	$0.09392	$0.08970	$0.07957
			Maximum	$12.78	$10.10	$6.17	Off Peak	$0.07394	$0.07375	$0.06886

- Spikes in grid demand are an expensive utilities hurdle
- Utility rates promote temporally smooth power demand.
- Larger users are charged more for spikes in demand.

Value of Peak Power (PG&E)

Rate Schedule	Customer Charge	Season	Time-of-Use Period	Demand Charge (per kW)			Time-of-Use Period	Total Energy Charge (per kWh)		
				Secondary	Primary	Transmission		Secondary	Primary	Transmission
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E-19 TOU (Time of Use): commercial customers, 499 kW max demand or more

- Secondary: customer receives end-use voltage and owns no transformers
- Primary: customer receives mid-voltages, and owns some transformers
- Transmission: customer receives transmission voltage and owns all transformers

Example Annual Power Analysis

Usage	WINTER USAGE (kWh)			SUMMER USAGE (kWh)				Monthly Charges
	Peak	Partial Peak	Off-Peak	Peak	Partial Peak	Off-Peak	Monthly Total	($)
January	-	344,604	506,659	-	-	-	851,263	$ 69,828
February	-	317,558	491,203	-	-	-	808,762	$ 66,145
March	-	362,602	608,532	-	-	-	971,134	$ 79,050
April	-	309,523	473,856	-	-	-	783,379	$ 64,107
May	-	-	-	144,749	193,104	488,160	826,013	$ 74,661
June	-	-	-	122,438	166,146	507,043	795,627	$ 70,078
July	-	-	-	142,080	194,784	513,629	850,493	$ 76,241
August	-	-	-	135,494	186,019	513,408	834,922	$ 74,398
September	-	-	-	134,074	179,962	526,253	840,288	$ 74,495
October	-	-	-	156,173	203,885	519,120	879,178	$ 79,574
November	-	299,693	481,978	-	-	-	781,670	$ 63,785
December	-	316,915	508,531	-	-	-	825,446	$ 67,365
Total	-	1,950,895	3,070,760	835,008	1,123,899	3,067,613	10,048,176	$ 859,728

Rigorous accounting is performed on 15-min increment load data

Demand	WINTER DEMAND (maximum demand per rate			SUMMER DEMAND (maximum			Monthly & Yearly	Peak demand charges	Partial peak demand charges	Mothly maximum demand charges
	Peak	Partial Peak	Off-Peak	Peak	Partial Peak	Off-Peak				
January	-	1,882	1,843	-	-	-	1,882	$ -	$ 414	$ 24,047
February	-	1,805	1,766	-	-	-	1,805	$ -	$ 397	$ 23,065
March	-	1,920	1,843	-	-	-	1,920	$ -	$ 422	$ 24,538
April	-	1,574	1,574	-	-	-	1,574	$ -	$ 346	$ 20,121
May	-	-	-	1,459	1,766	1,728	1,766	$ 23,741	$ 6,677	$ 22,575
June	-	-	-	1,344	1,613	1,574	1,613	$ 21,867	$ 6,096	$ 20,612
July	-	-	-	1,382	1,690	1,766	1,766	$ 22,492	$ 6,387	$ 22,575
August	-	-	-	1,382	1,728	1,651	1,728	$ 22,492	$ 6,532	$ 22,084
September	-	-	-	1,459	4,992	1,805	4,992	$ 23,741	$ 18,870	$ 63,798
October	-	-	-	1,651	1,843	1,805	1,843	$ 26,865	$ 6,967	$ 23,556
November	-	1,574	1,574	-	-	-	1,574	$ -	$ 346	$ 20,121
December	-	1,651	1,651	-	-	-	1,651	$ -	$ 363	$ 21,102
Winter Season Maximum			1,920	Summer Season Maximu		4,992	4,992	$ 141,198	$ 53,818	$ 308,192

Dispatching peak shaving:

- ++ saves demand charges ($/kW)
- + saves energy charges ($/kWh)
- - - Increases MHE depreciation expense (decreasing vehicle life span)
- - increases hydrogen fuel expense (from MHEs)

Equipment Analysis Assumptions

Analysis inputs:

- MHE depreciable cost — power generation only
- Depreciation basis — hours of operation
- Vehicle power generation life — 10,000 hours
- Hydrogen to power efficiency — 13 kWh/kgH_2
- Power electronics & interconnect requires no maintenance
- MHE vehicles don't require maintenance associated with peak shaving, but their value is depreciated

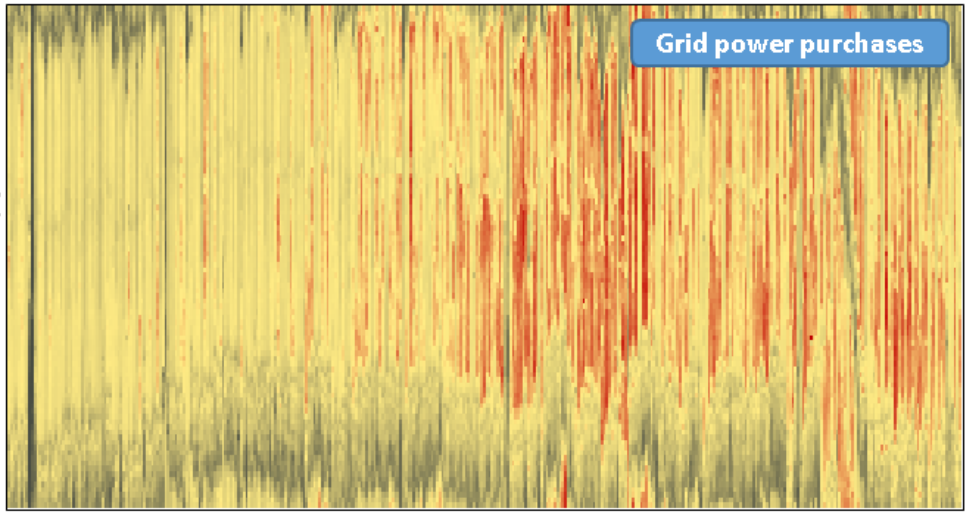
Analysis Scenarios

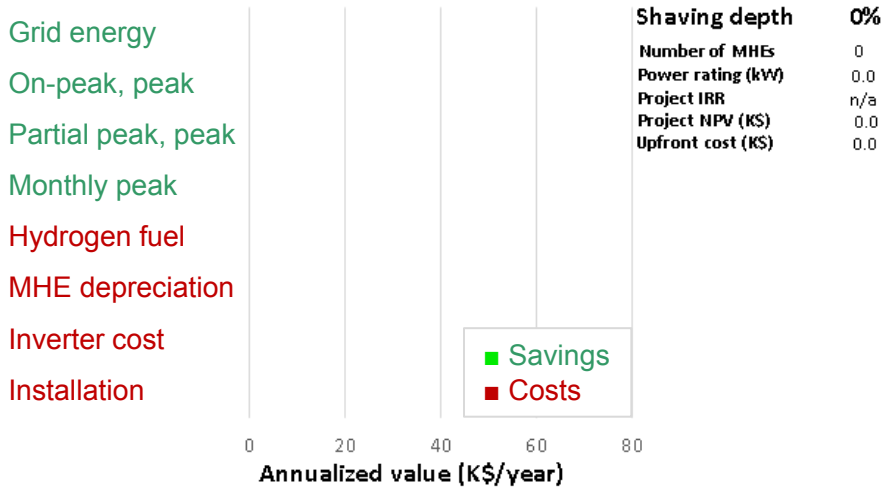
- 103 commercial scale metered, 15-min profiles
  - Mail distribution center
  - DOE facility
  - Anonymous food processing facility
  - Anonymous warehouse & office complex
  - 99 California commercial buildings

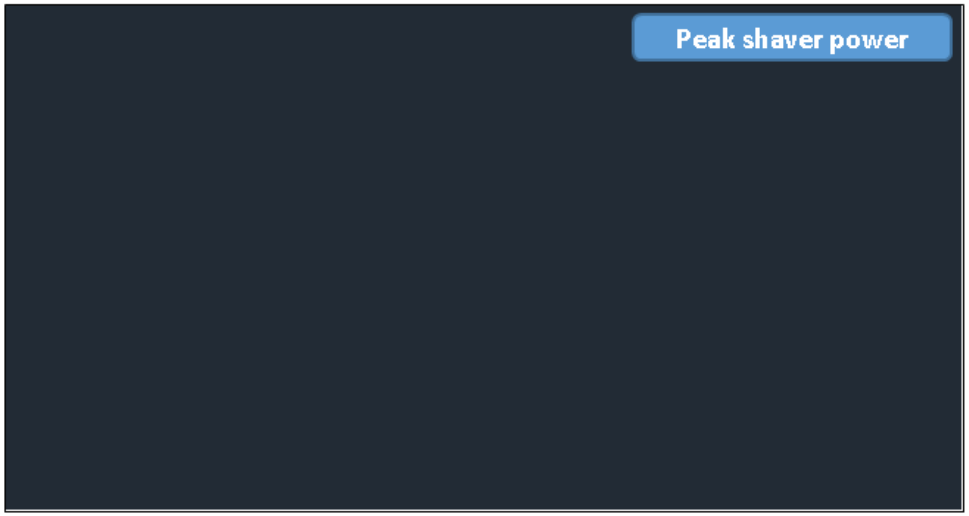
• Power output capacity per MHE	2.5, 5.0, **8.0**, 10.5	kW
• Max output power %	100%, **90%**, 80%	% of rated power
• MHE interconnect capital cost	0, **300**, 600	$/kW
• MHE interconnect installation cost	500, **1000**, 2000	$/MHE
• MHE depreciable cost	1500, **1000**, 667, 444, 296, 198, 132	$/kW
• Hydrogen cost	5, **7**, 9	$/kg
• Hydrogen available per vehicle each day	0.7, **1.0**, 1.8, 3, 19.4	kg
• Shaving depth (% of annual max)	0 to 20, **2**	%
• Analysis period	15	years
• Discount rate	10%	
• Escalation rate of costs	2%	annually
• Analysis metrics	IRR, NPV	

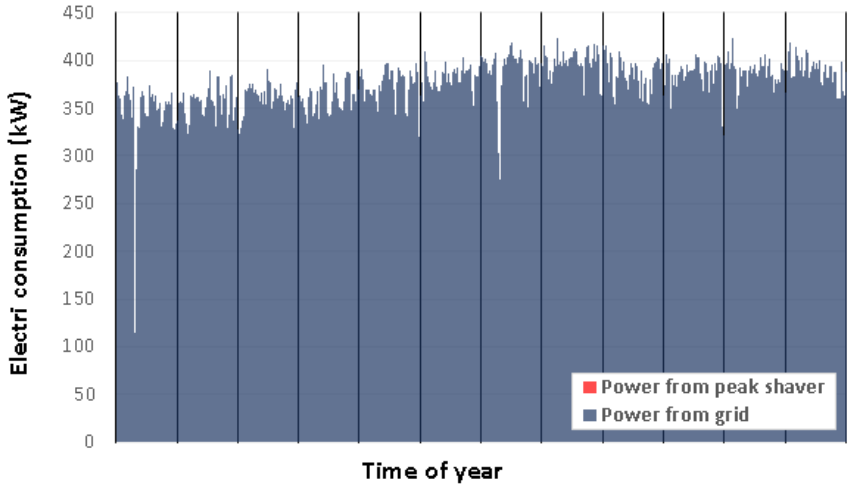
Values in GREEN: baseline conditions in sensitivity analysis

Example Peak Shaving









- "less is more" – costs increase faster than expenses with increase in shaving depth
- Note: this example assumes MHE active refueling (never run out of fuel)

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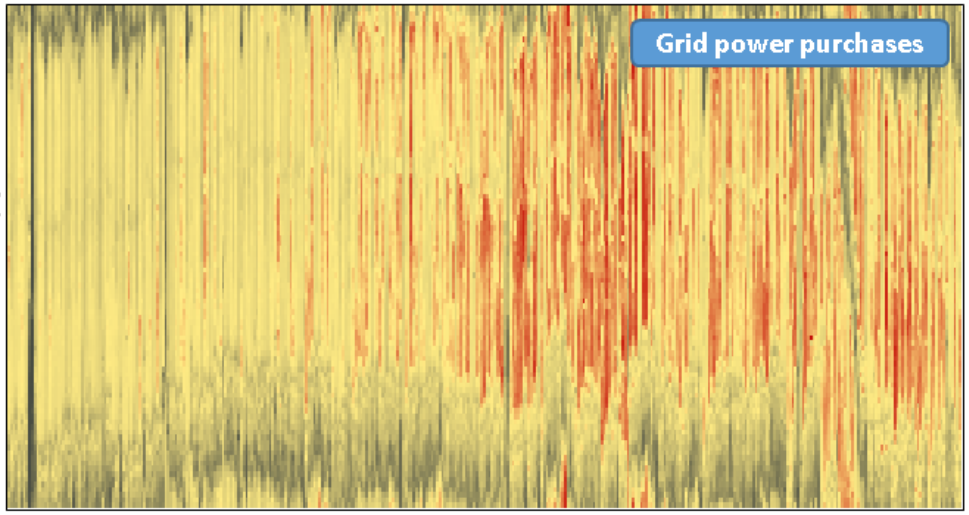

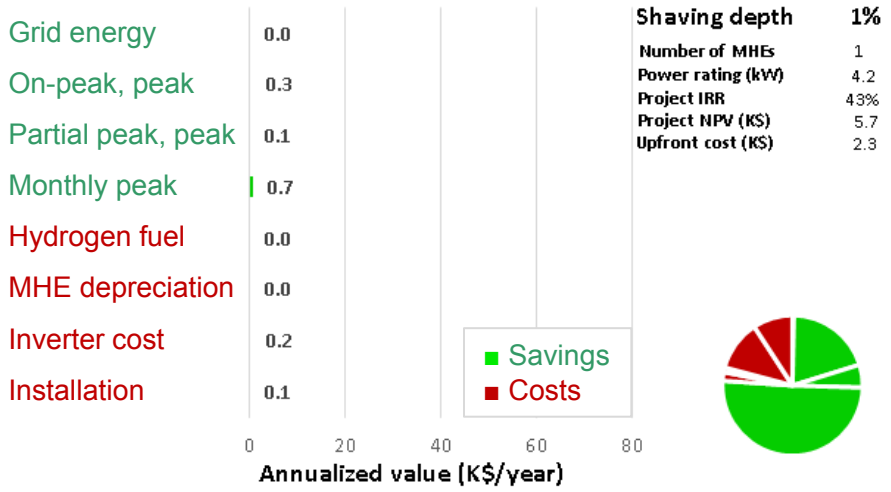

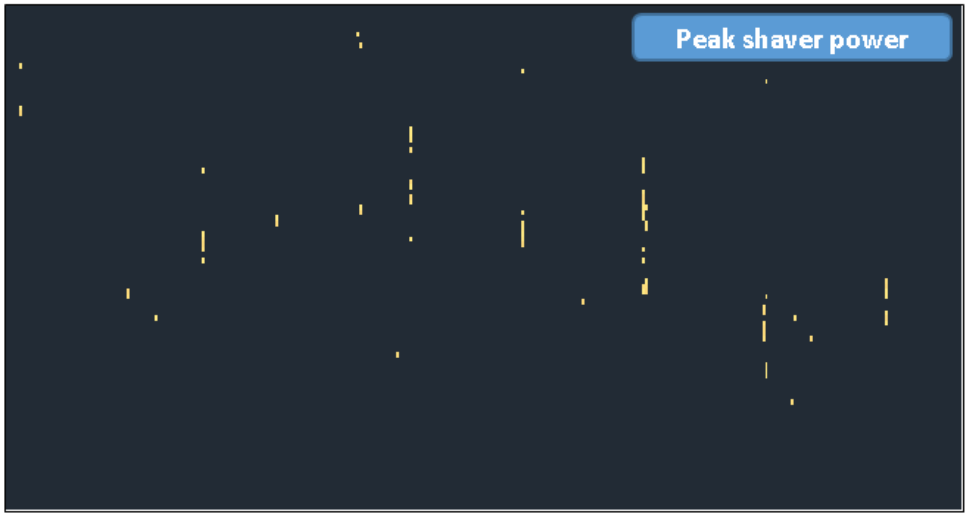

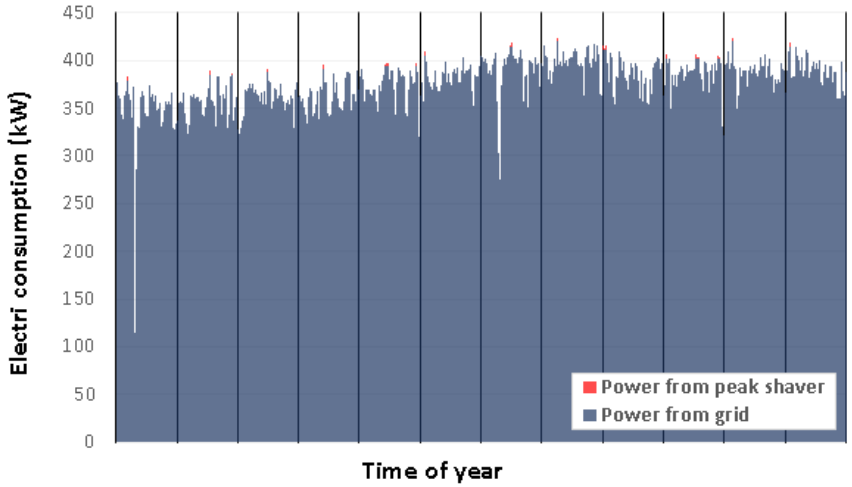

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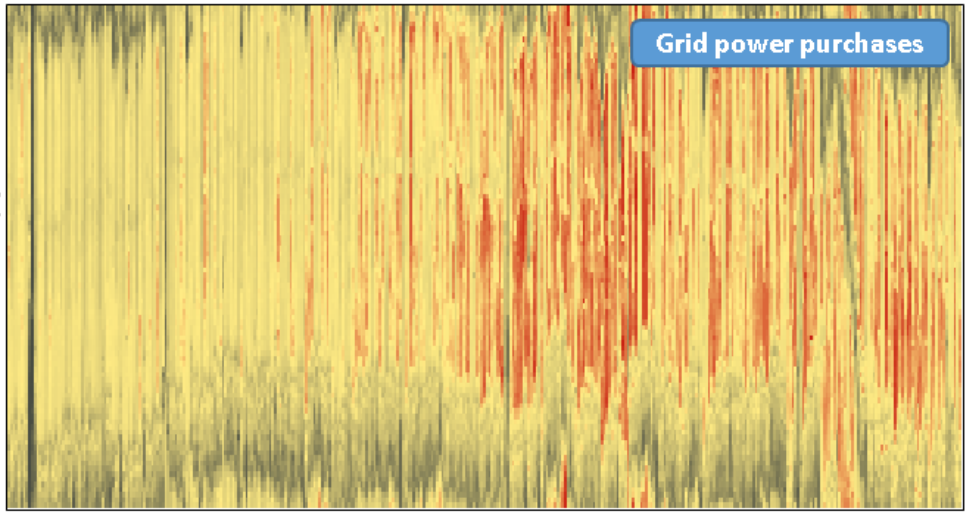

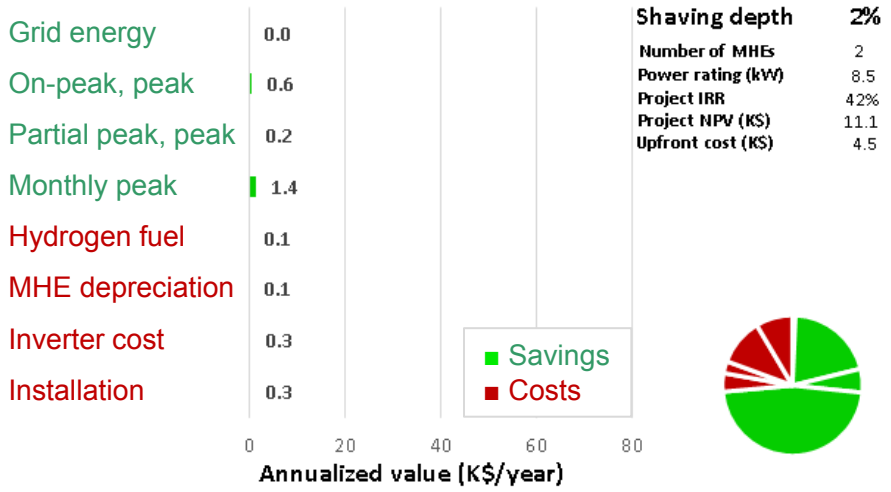

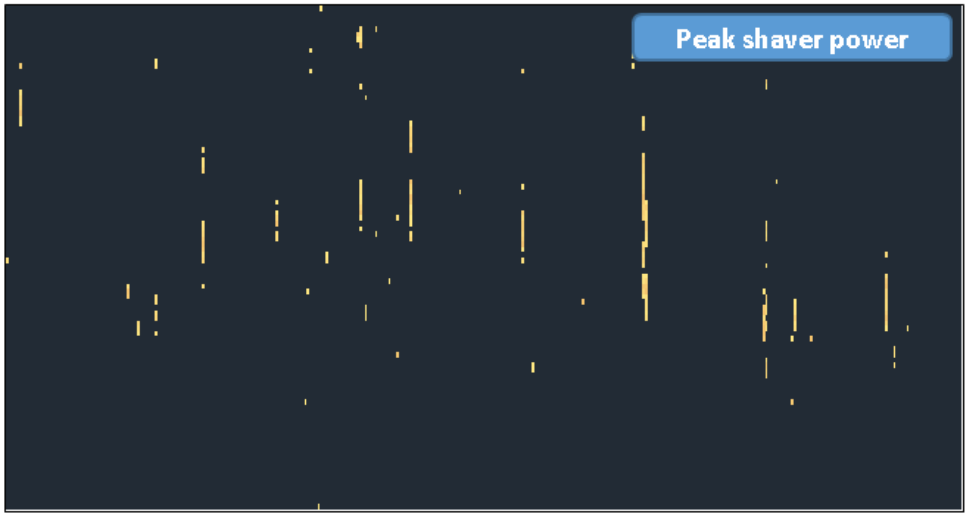

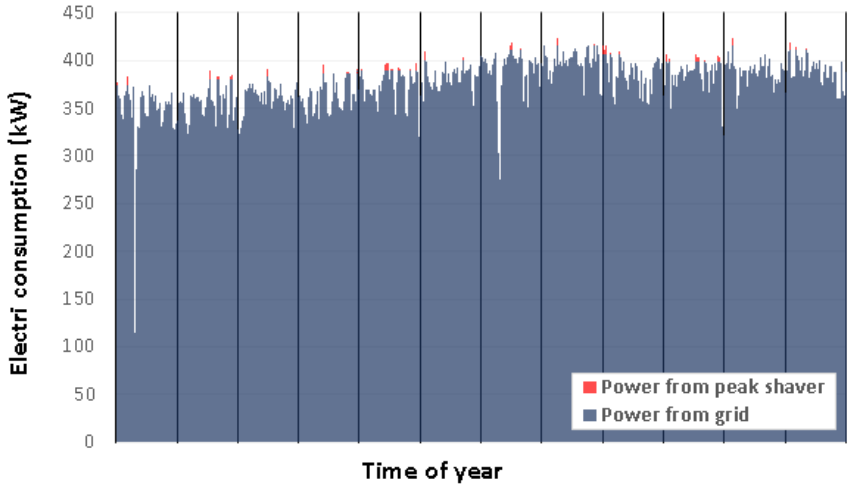

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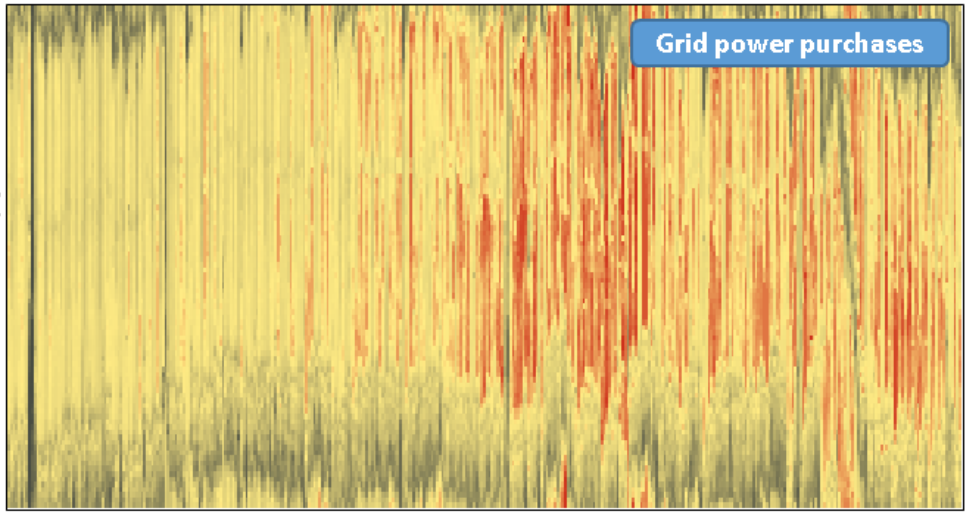

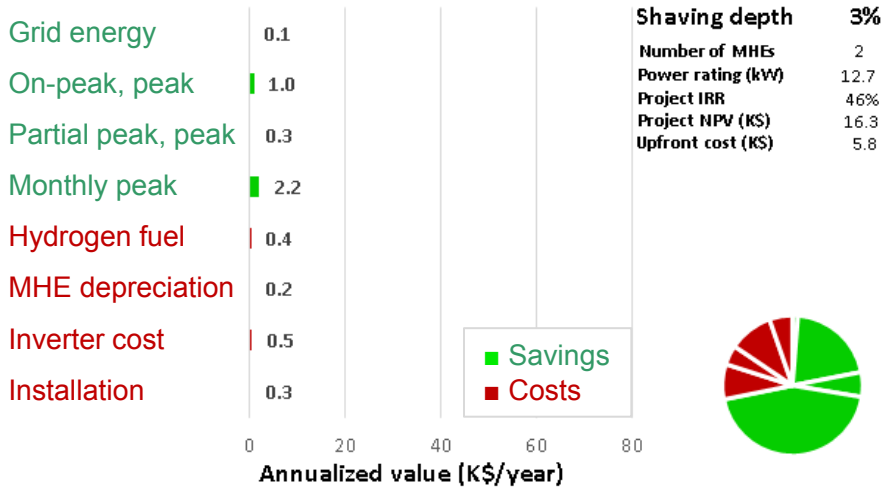

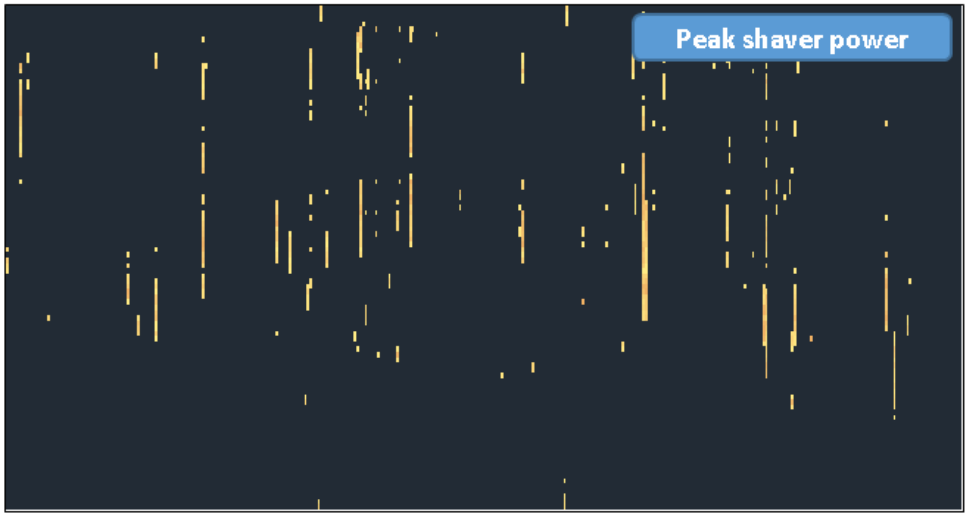

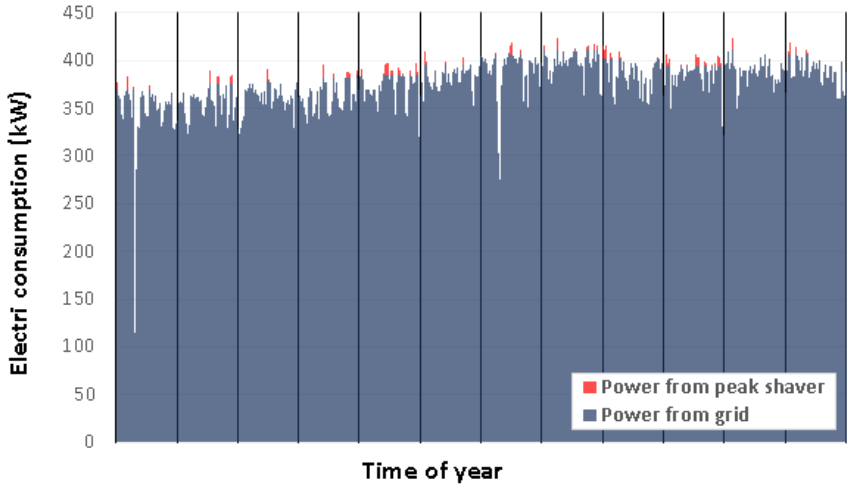

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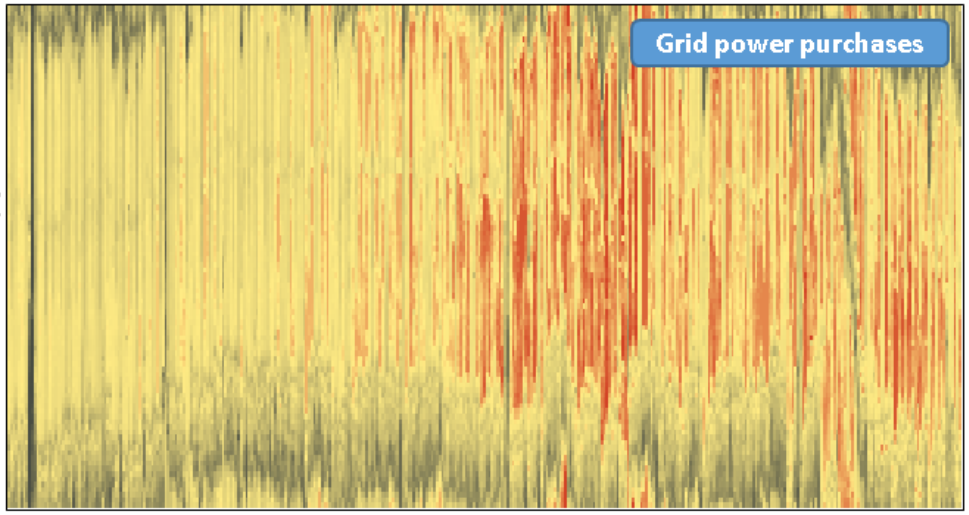

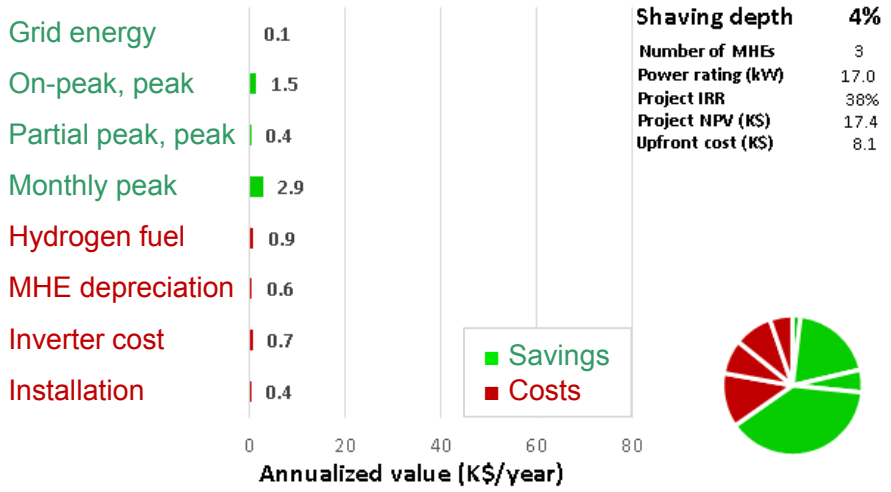

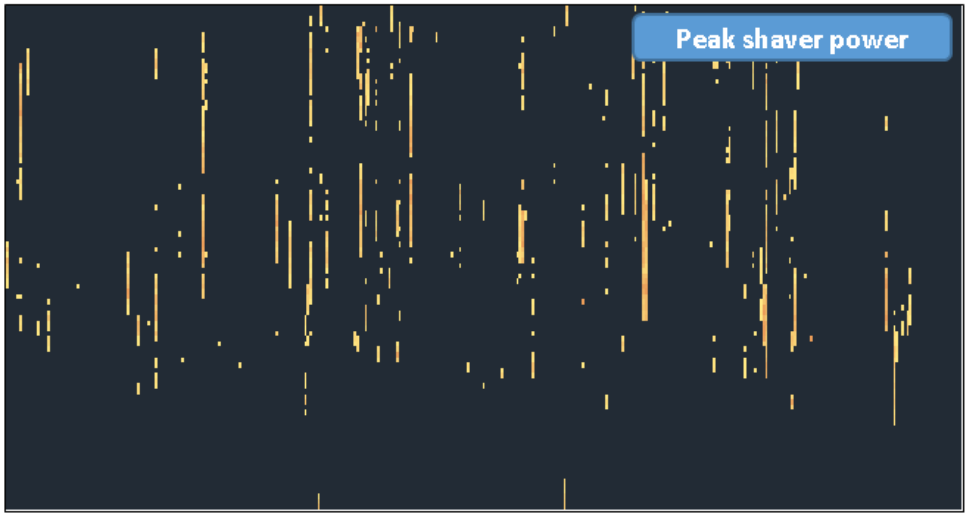

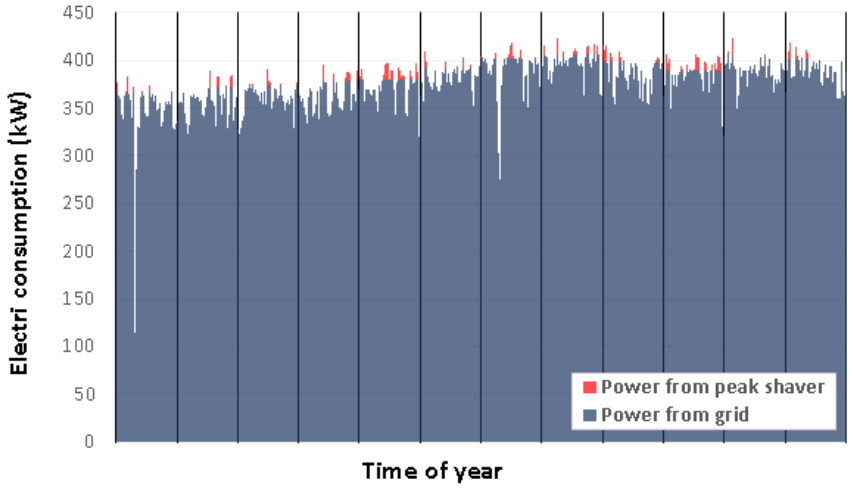

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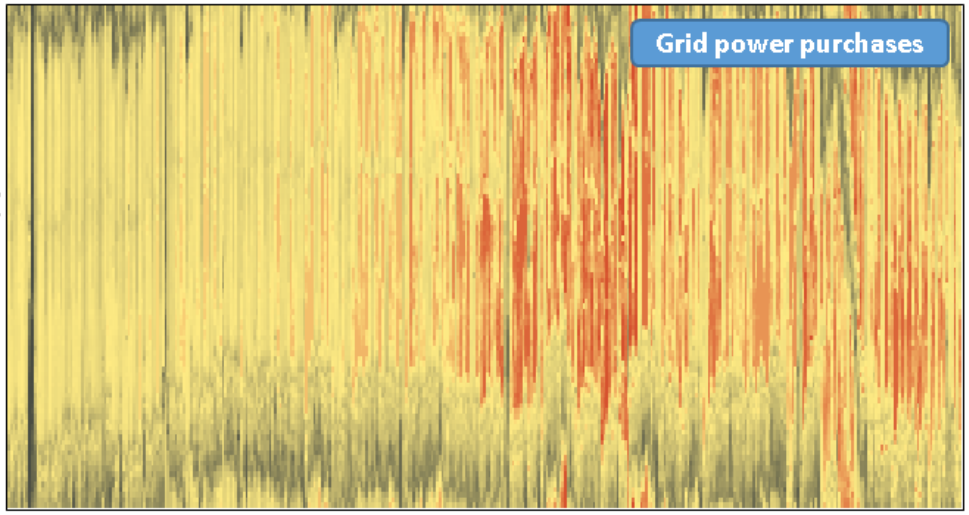

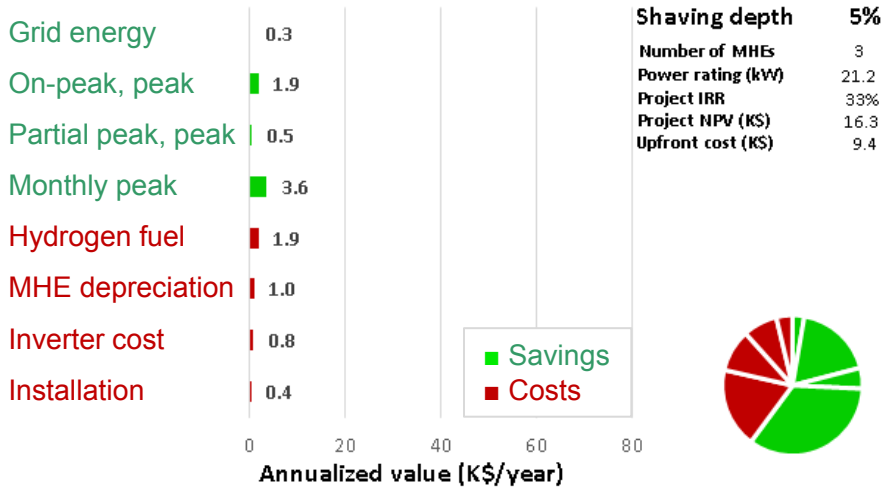

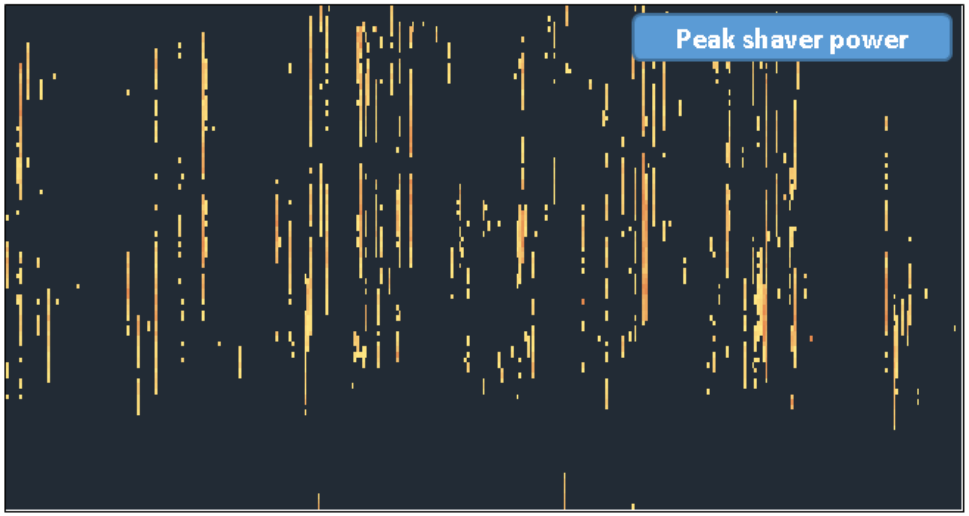

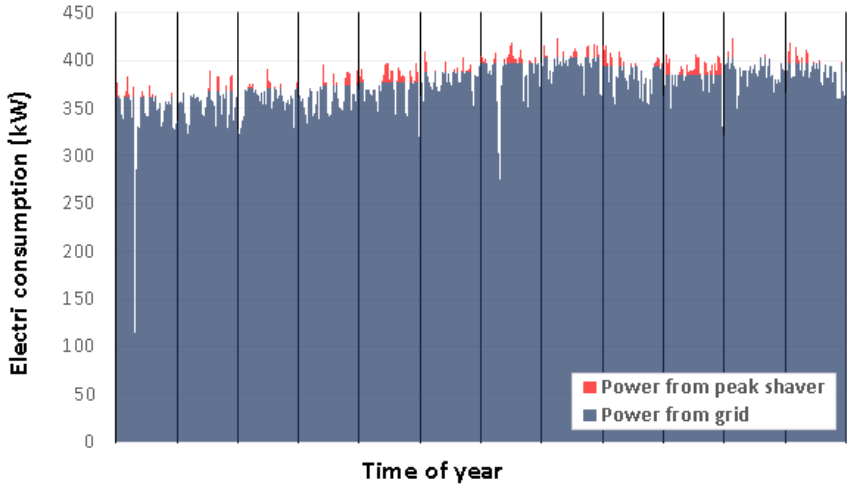

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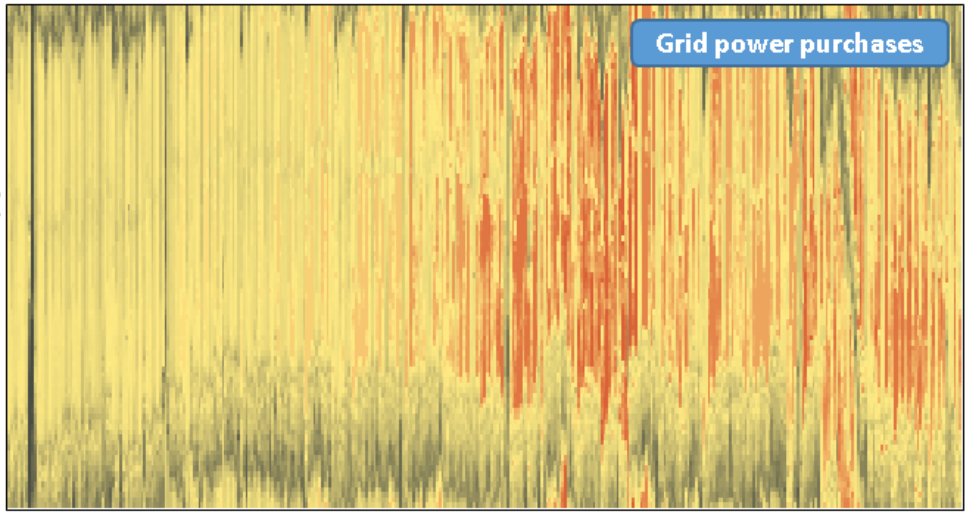

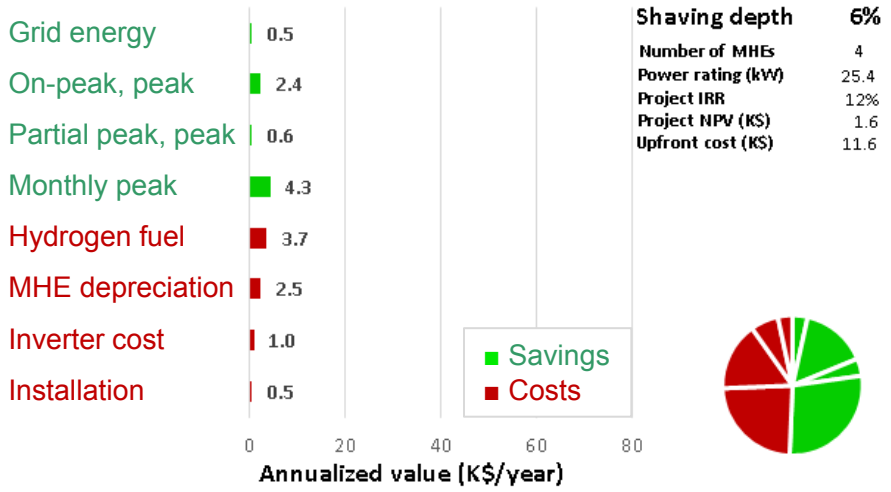

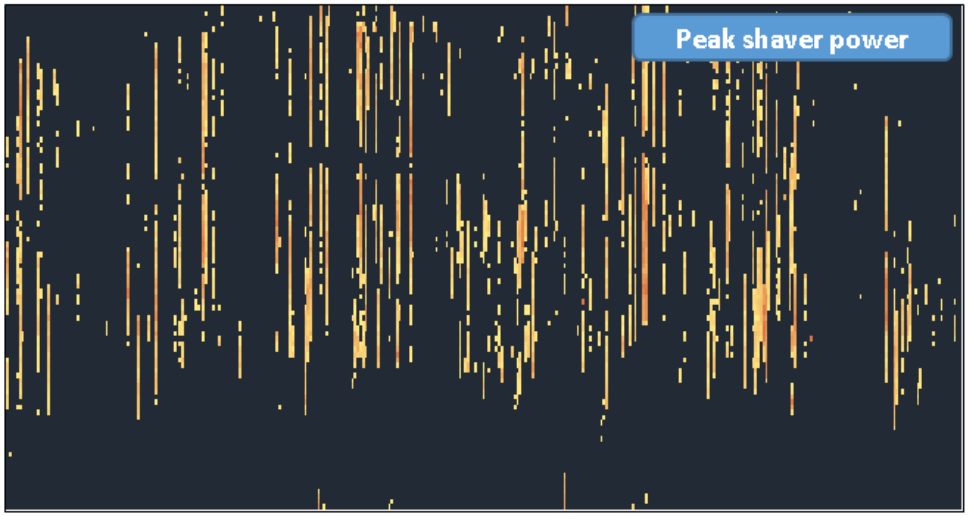

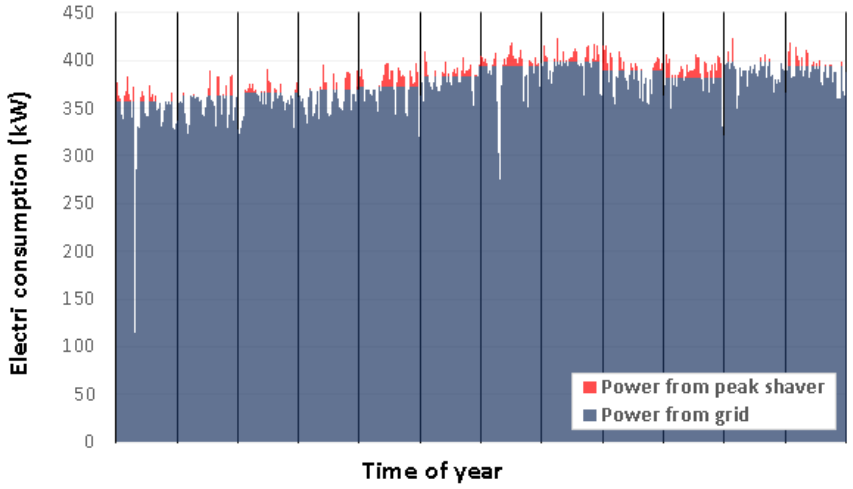

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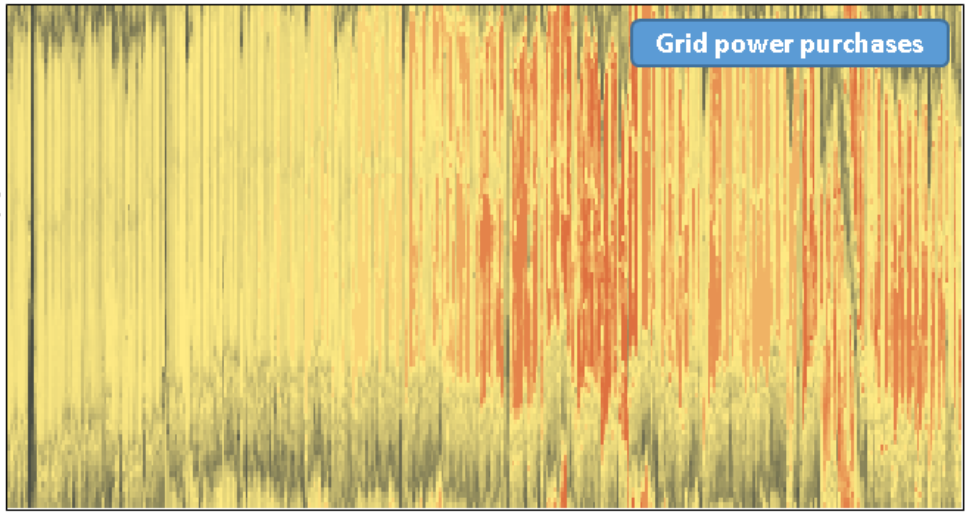

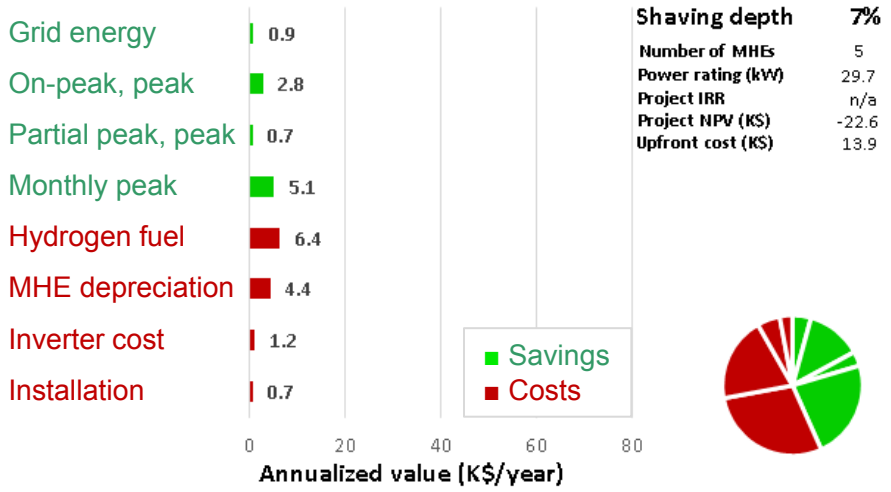

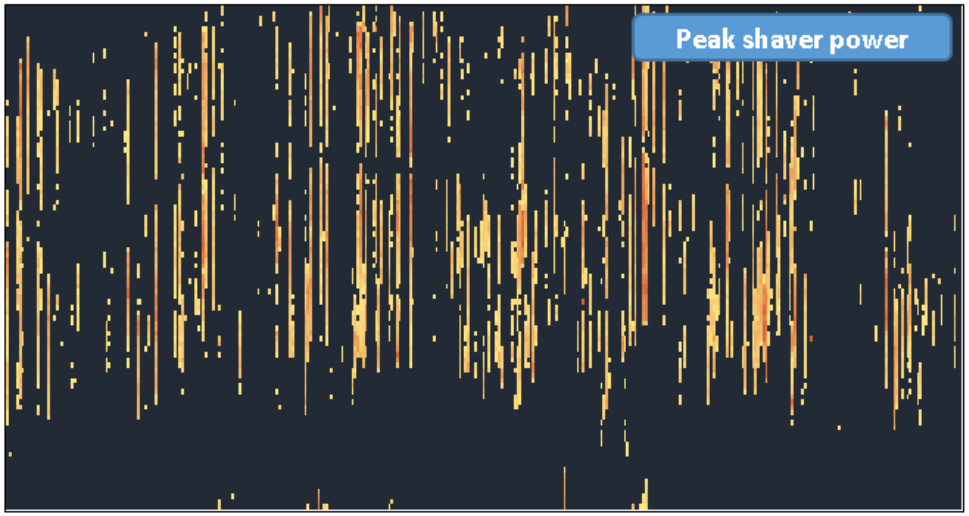

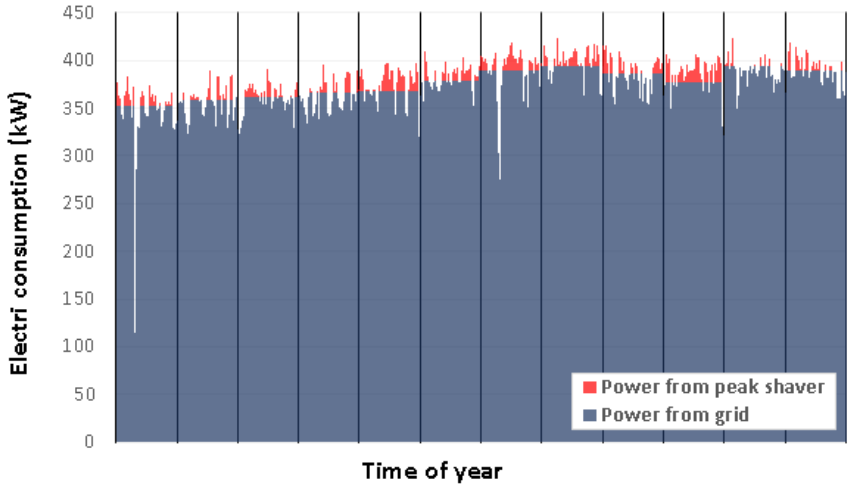

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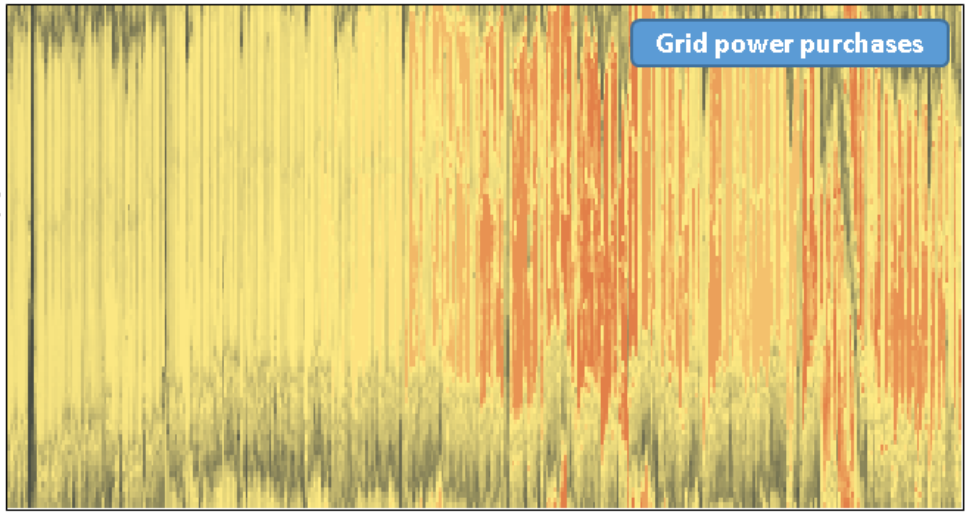
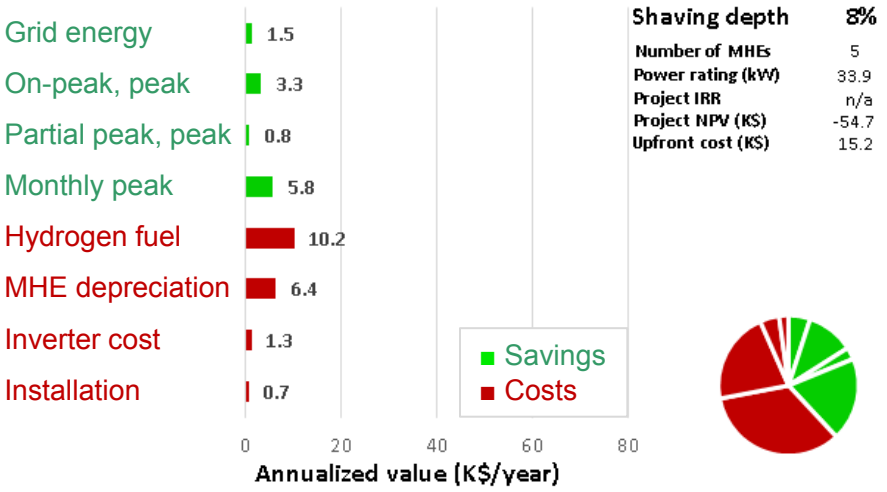
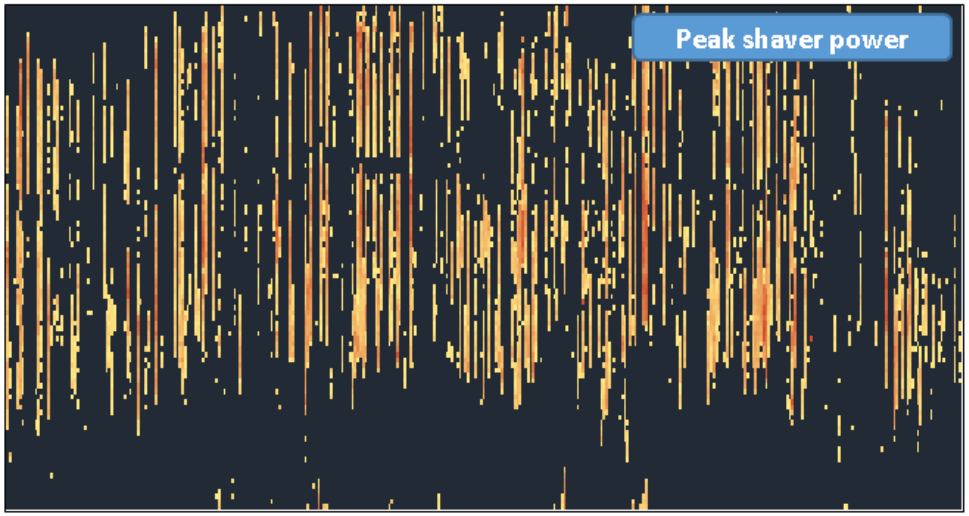
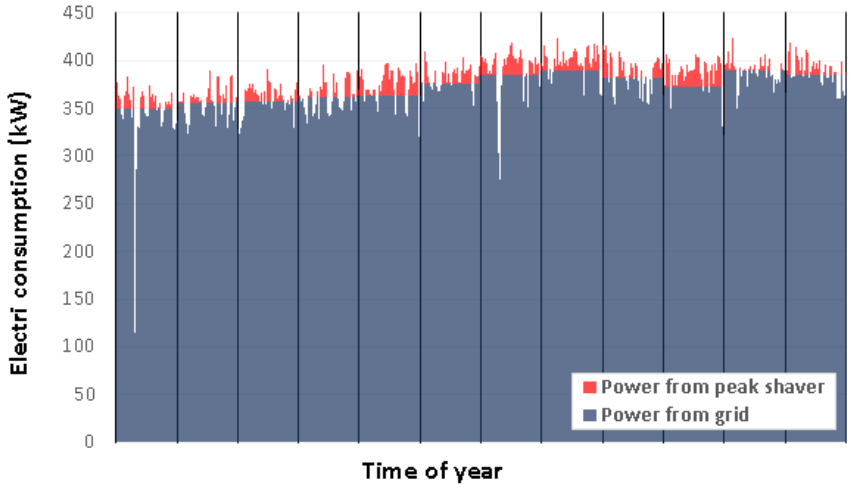
Example Peak Shaving









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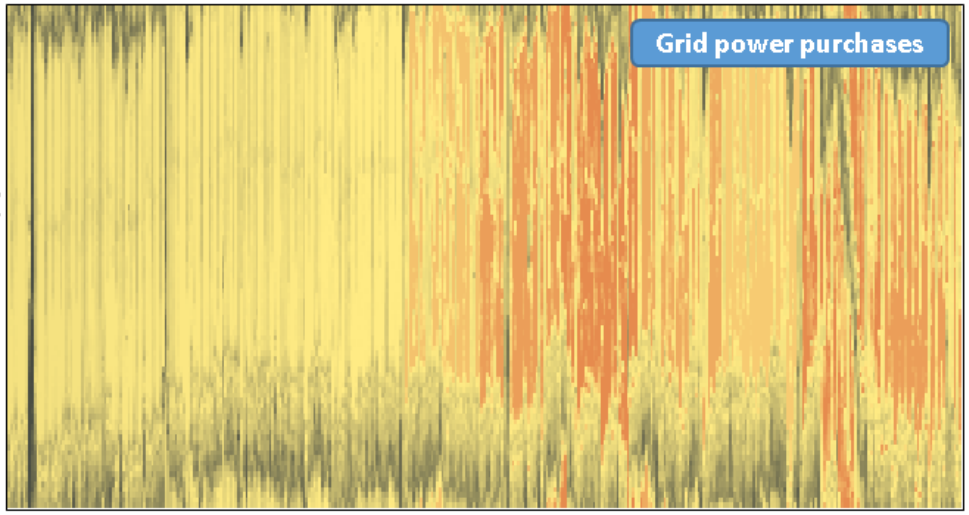

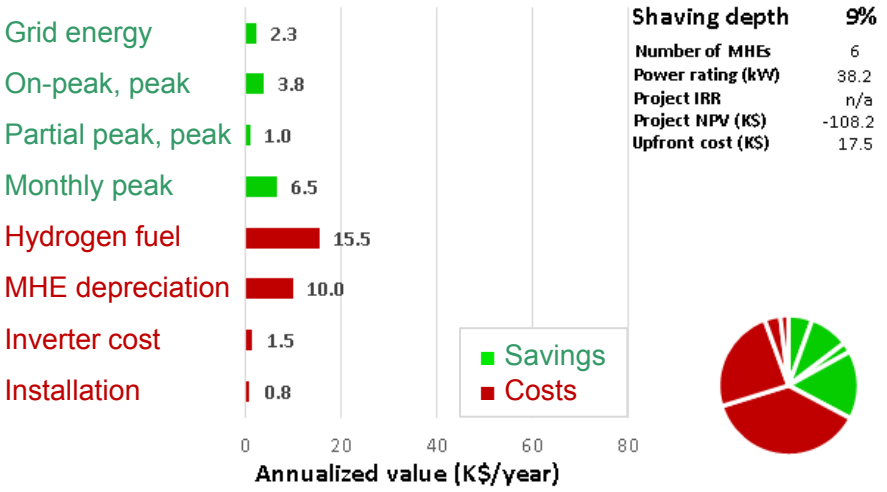

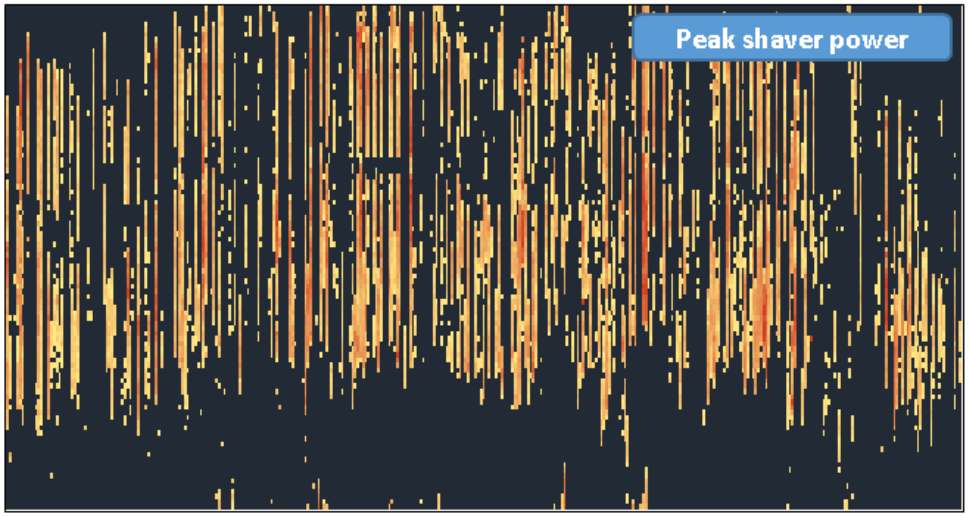

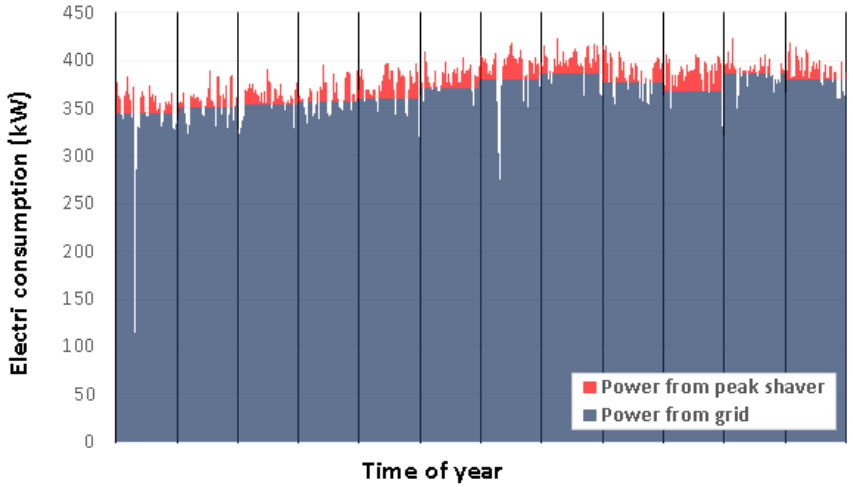

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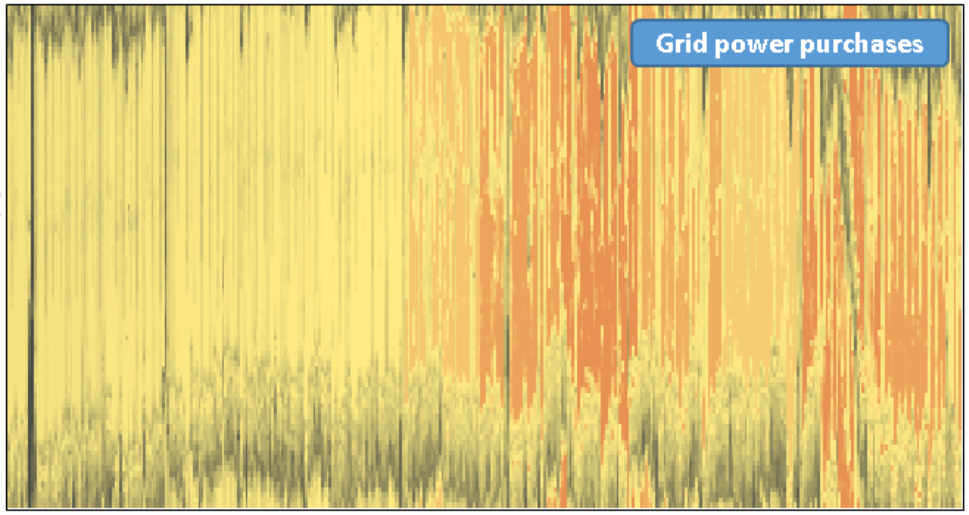
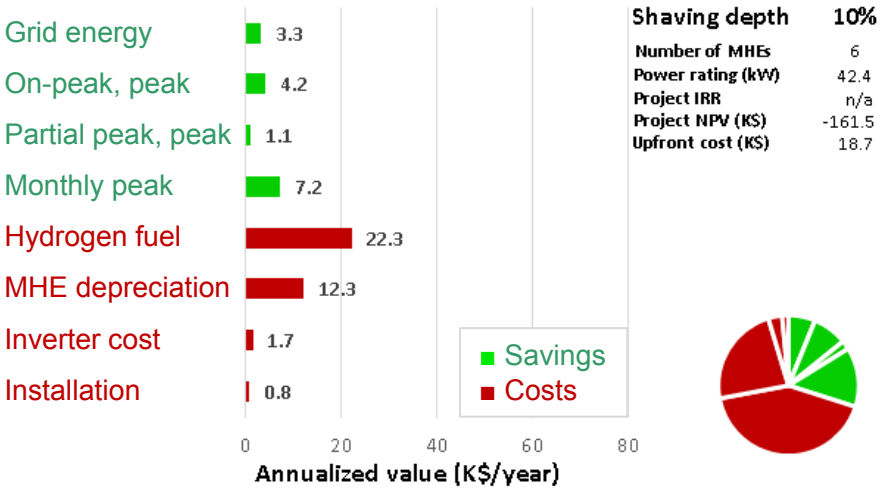
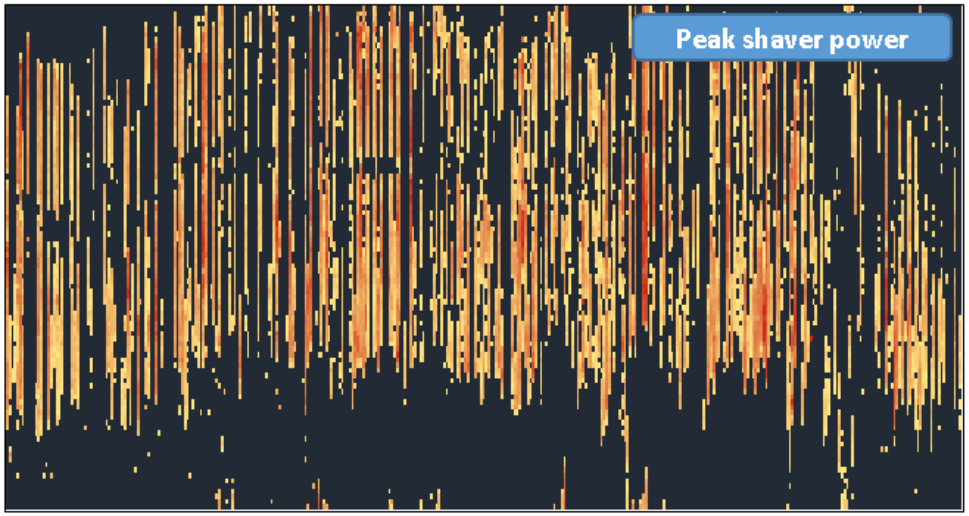
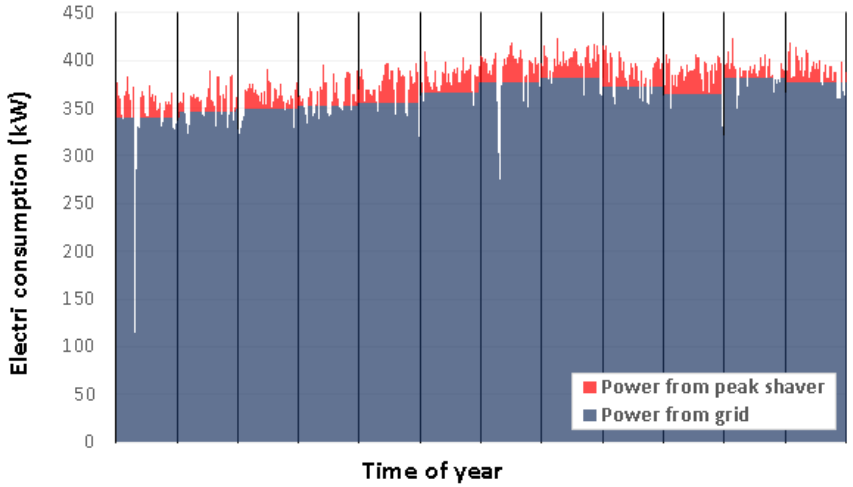
Example Peak Shaving









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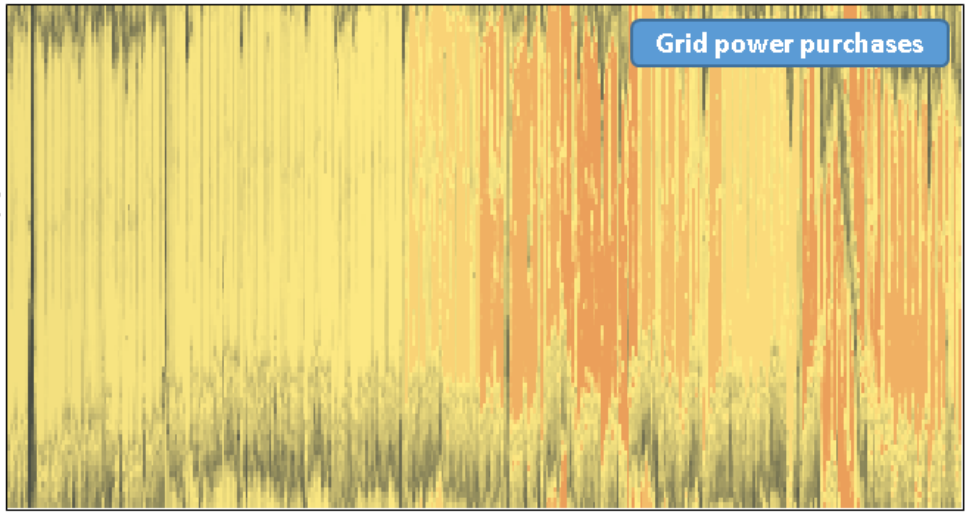

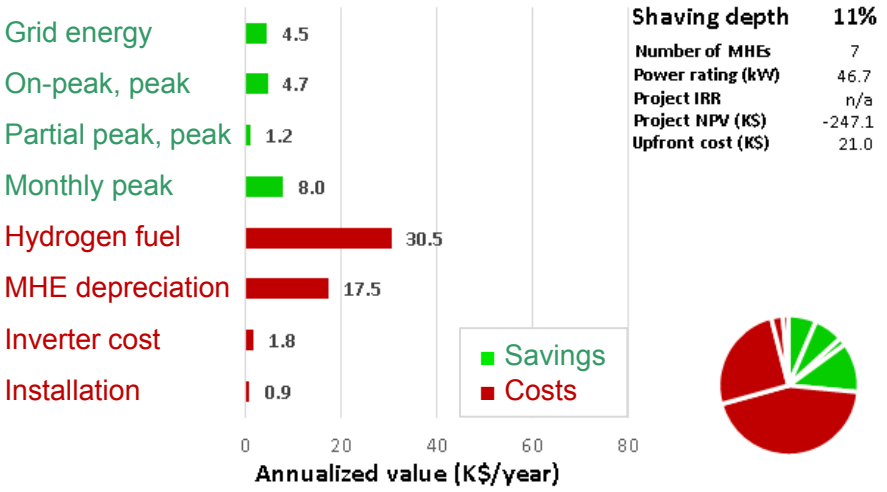

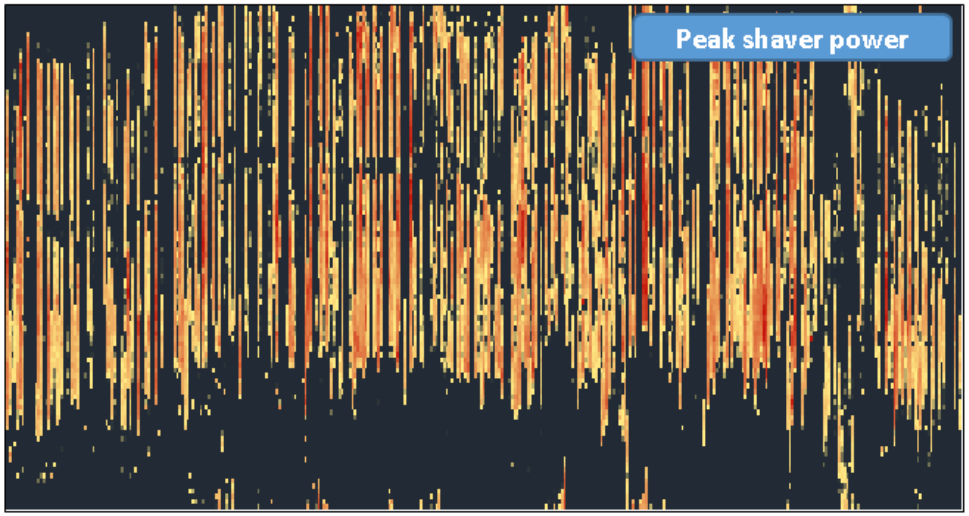

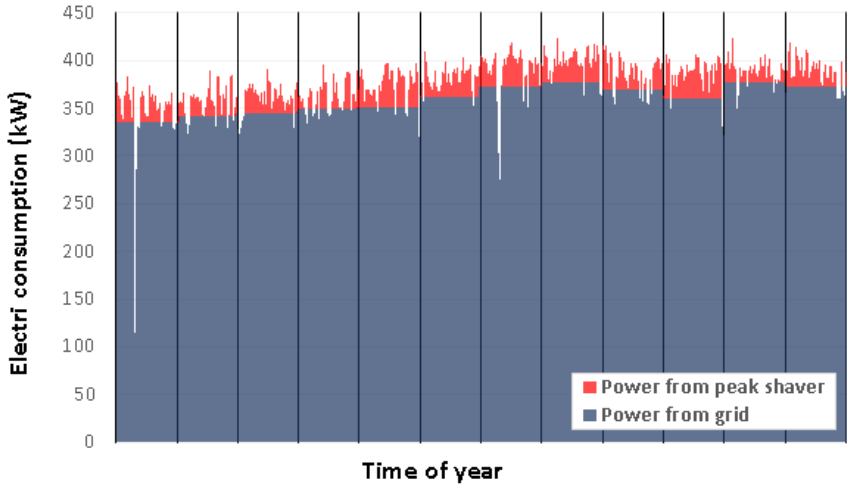

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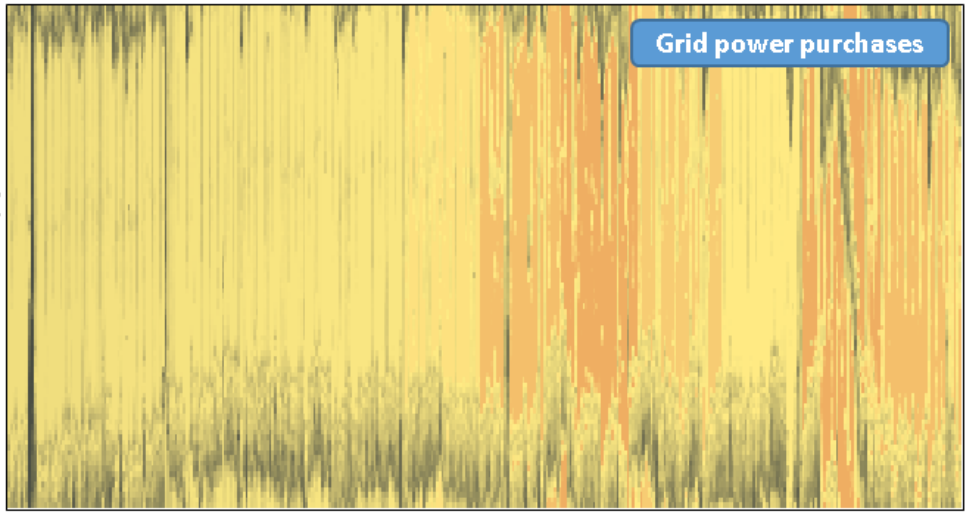
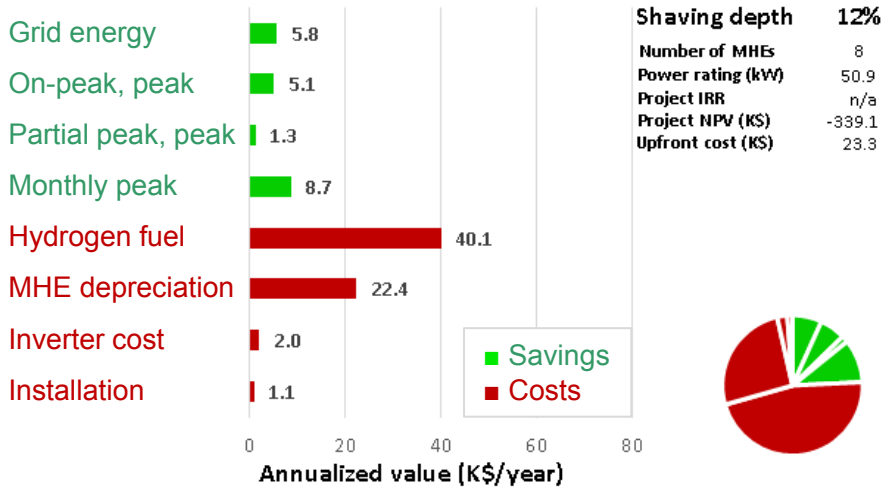
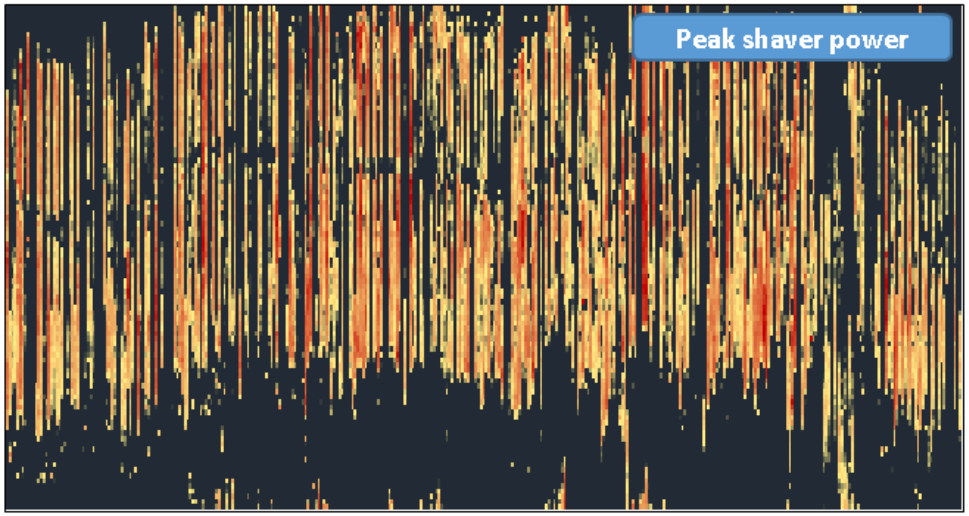
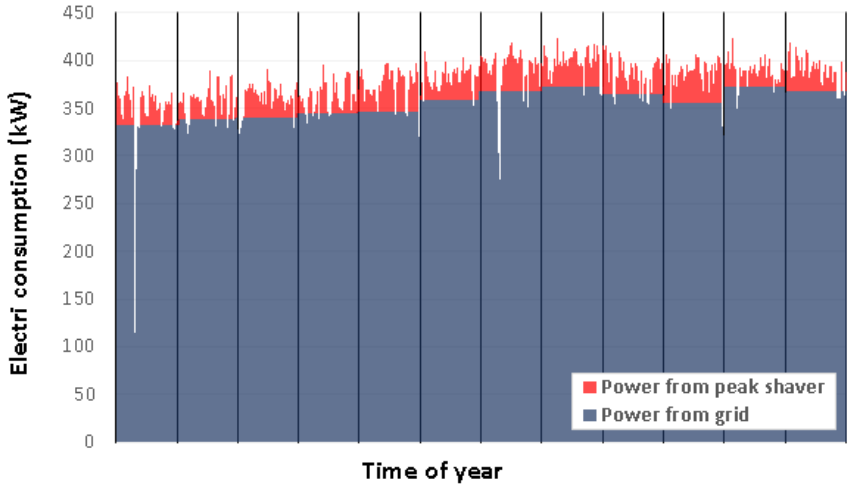
Example Peak Shaving









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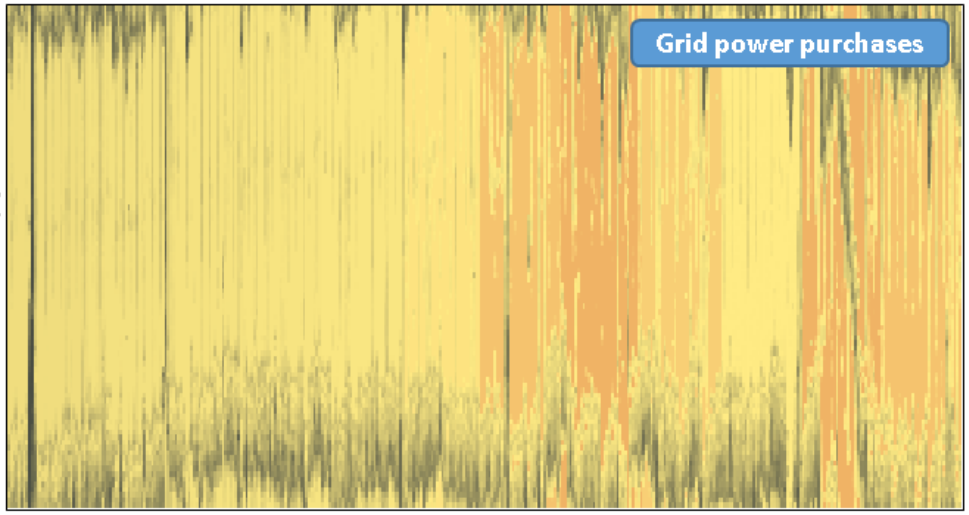

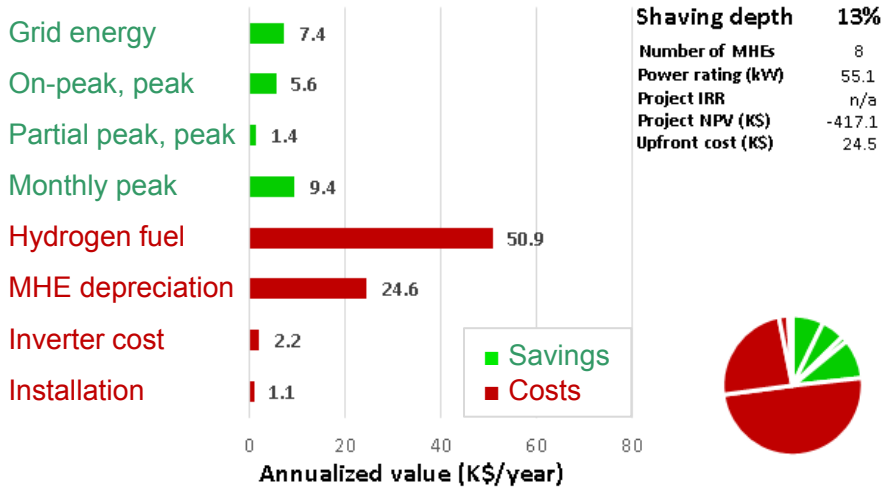

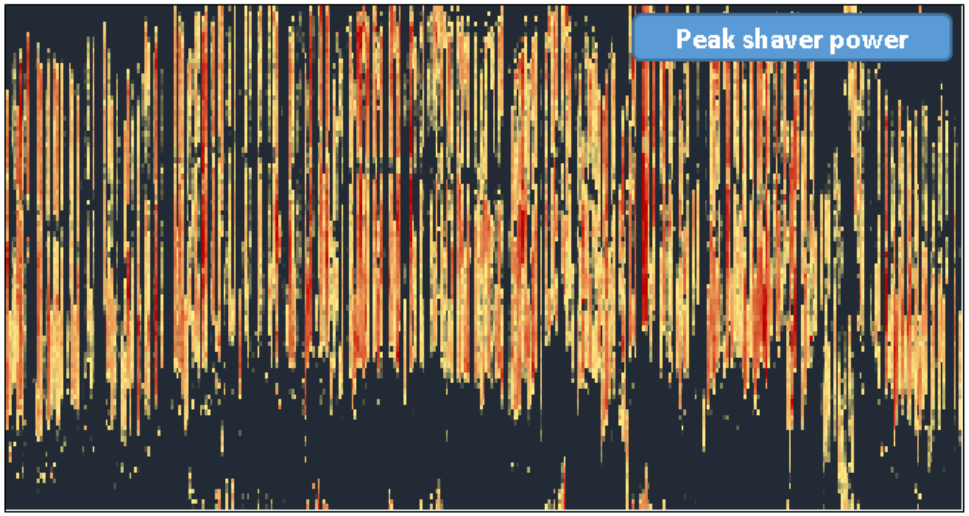

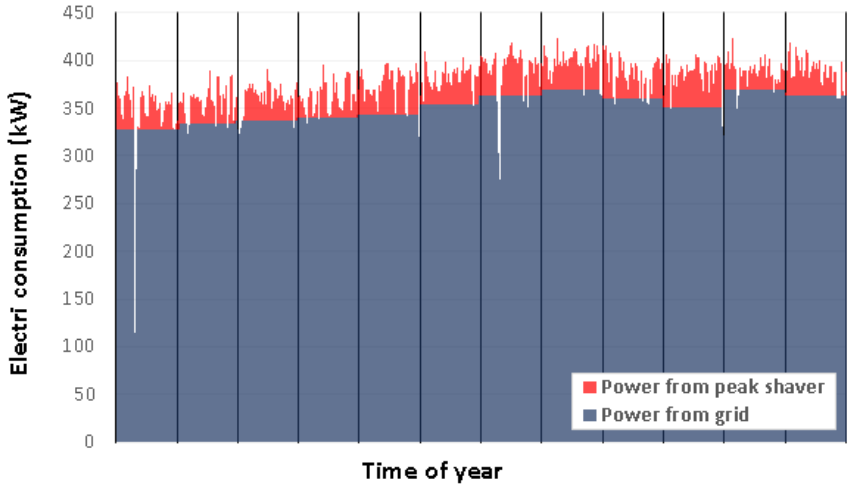

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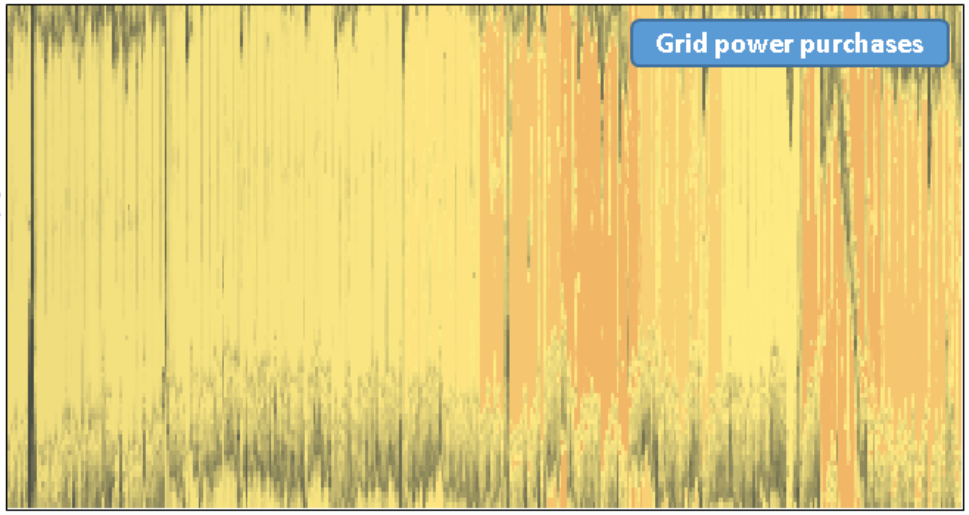
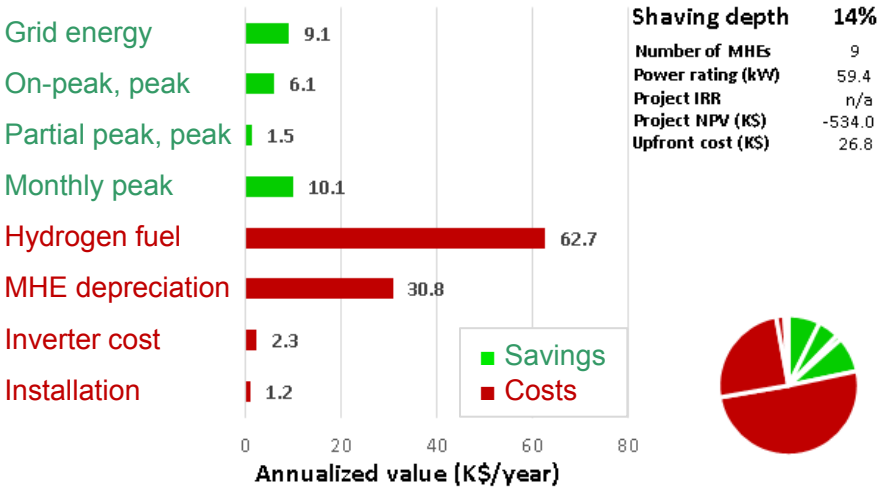
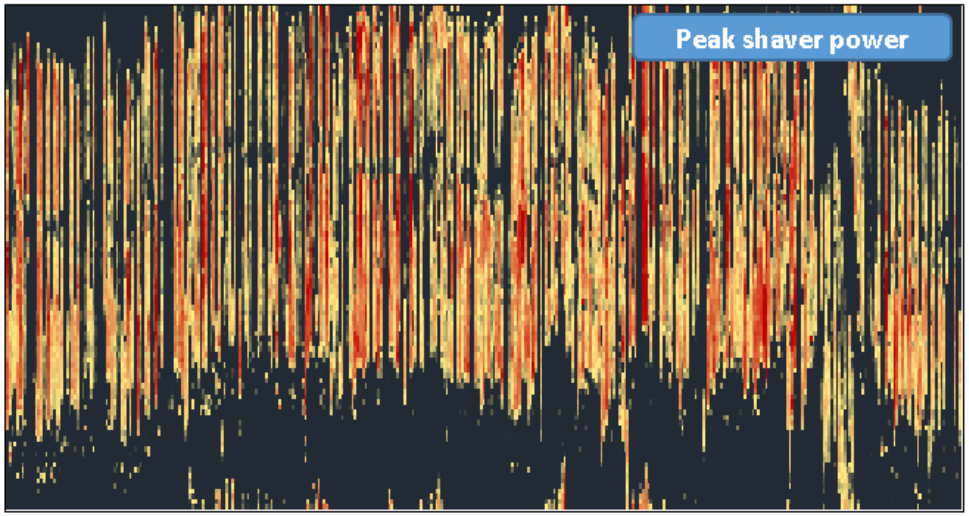
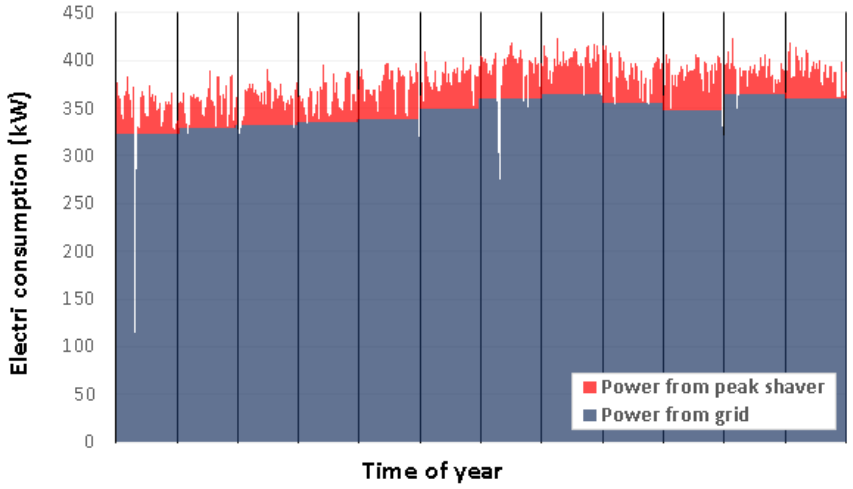
Example Peak Shaving









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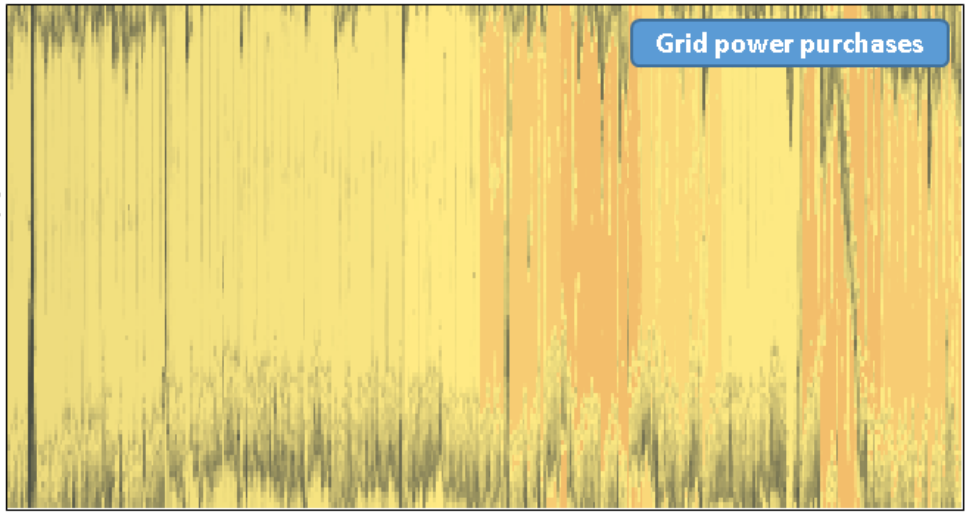

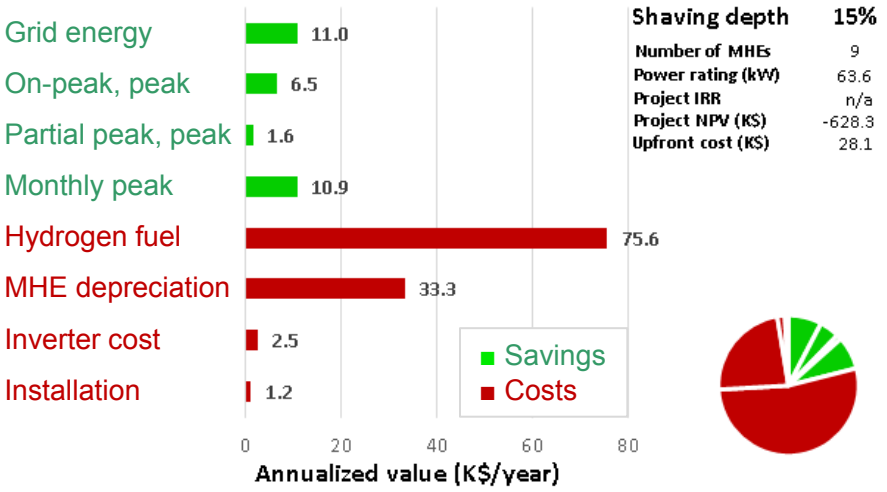

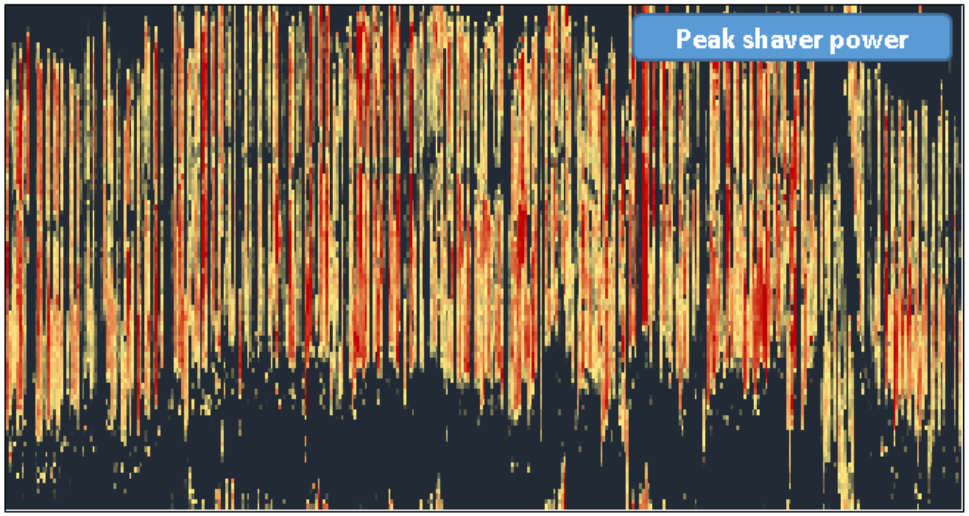

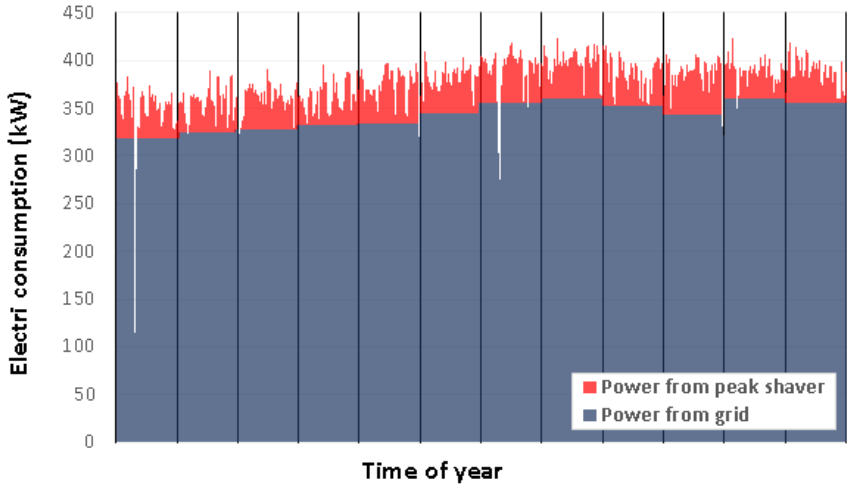

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Example Analysis

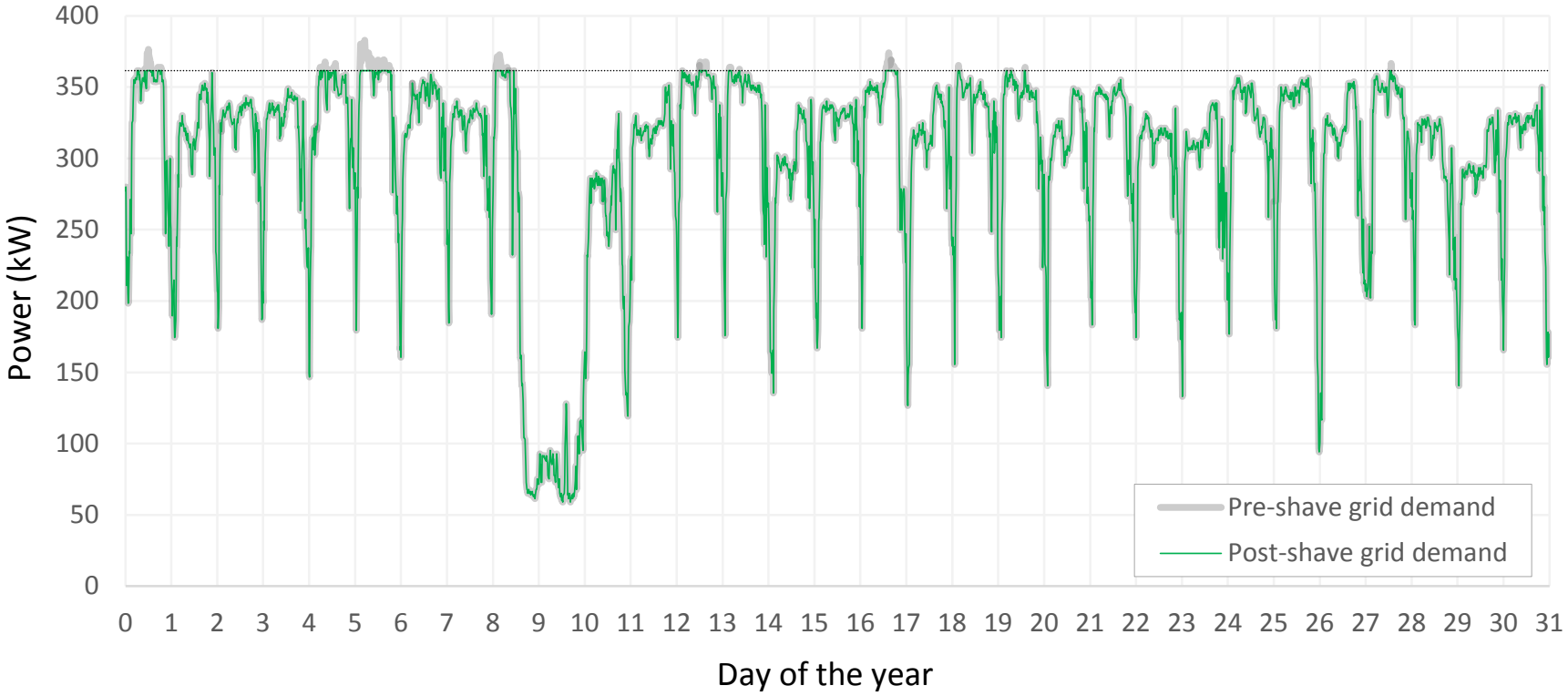
Profile #5

• Load profile average demand:	328 kW
• Annual peak:	424 kW
• Shaving demand (2% of peak)	8.5 kW

Equipment

• Number of MHEs	2
• Maximum hydrogen per MHE	1.0 kg/day
• Maximum energy per MHE	26 kWh/day
• Power electronics rating	8.5 kW
• Interconnect cap cost (@$300/kW)	$2,545
• Installation cap cost (@$1,000/MHE)	$2,000
• Project up-front cap cost	$4,545

Example Analysis



Step 1: Analysis is performed on energy consumption impacts

- Annual energy provided 190 kWh
- Annual hours of MHE operation 53.0 h
- Hydrogen consumed 14.6 kg

Grid Expense Analysis

Grid billing without peak shaving

Usage	WINTER USAGE (kWh) Peak	Partial Peak	Off-Peak	SUMMER USAGE (kWh) Peak	Partial Peak	Off-Peak	Monthly Total	Monthly Charges ($)
January	-	91,730	132,997	-	-	-	224,727	$ 18,449
February	-	83,944	124,463	-	-	-	208,407	$ 17,087
March	-	88,329	145,488	-	-	-	233,818	$ 19,053
April	-	91,621	137,469	-	-	-	229,090	$ 18,769
May	-	-	-	49,057	51,752	143,943	244,752	$ 22,419
June	-	-	-	42,713	45,501	151,738	239,951	$ 21,428
July	-	-	-	49,805	55,081	150,934	255,820	$ 23,353
August	-	-	-	48,621	53,943	155,571	258,135	$ 23,395
September	-	-	-	45,518	48,974	148,862	243,354	$ 21,977
October	-	-	-	49,717	52,657	143,242	245,617	$ 22,555
November	-	94,473	146,096	-	-	-	240,569	$ 19,675
December	-	103,996	141,276	-	-	-	245,272	$ 20,213
Total	-	554,093	827,789	285,431	307,908	894,289	2,869,510	$ 248,373

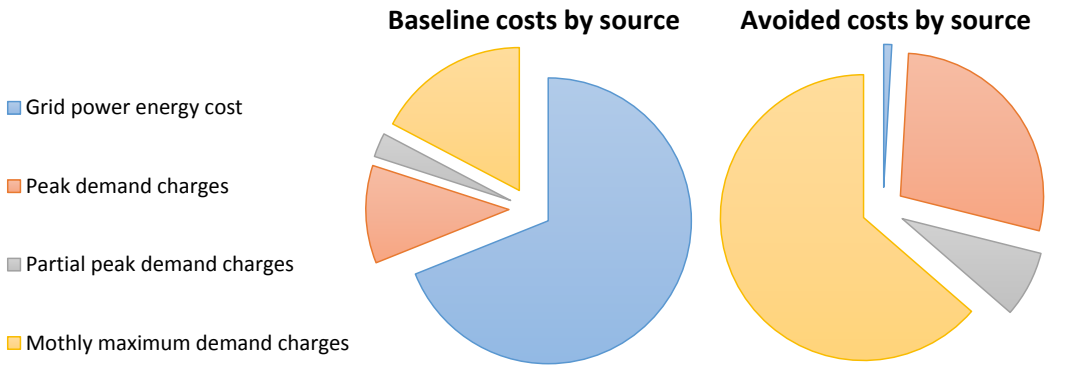
Demand	WINTER DEMAND (maximum Peak	Partial Peak	Off-Peak	SUMMER DEMAND (maximum Peak	Partial Peak	Off-Peak	Monthly & Yearly	Peak demand charges	Partial peak demand charges	Mothly maximum
January	-	376	383	-	-	-	383	$ -	$ 83	$ 4,892
February	-	385	389	-	-	-	389	$ -	$ 85	$ 4,972
March	-	378	392	-	-	-	392	$ -	$ 83	$ 5,004
April	-	388	395	-	-	-	395	$ -	$ 85	$ 5,052
May	-	-	-	397	398	397	398	$ 6,452	$ 1,504	$ 5,084
June	-	-	-	395	409	409	409	$ 6,432	$ 1,546	$ 5,228
July	-	-	-	413	419	415	419	$ 6,717	$ 1,584	$ 5,357
August	-	-	-	424	415	417	424	$ 6,901	$ 1,570	$ 5,421
September	-	-	-	415	413	415	415	$ 6,758	$ 1,561	$ 5,309
October	-	-	-	407	405	407	407	$ 6,615	$ 1,532	$ 5,196
November	-	424	409	-	-	-	424	$ -	$ 93	$ 5,421
December	-	419	410	-	-	-	419	$ -	$ 92	$ 5,357
	Winter Season Ma		424	Summer Season Maximu		424	424	$ 39,875	$ 9,819	$ 62,291

Grid billing with peak shaving

Usage	WINTER USAGE (kWh) Peak	Partial Peak	Off-Peak	SUMMER USAGE (kWh) Peak	Partial Peak	Off-Peak	Monthly Total	Monthly Charges ($)
January	-	91,729	132,989	-	-	-	224,718	$ 18,448
February	-	83,938	124,458	-	-	-	208,396	$ 17,086
March	-	88,329	145,474	-	-	-	233,804	$ 19,052
April	-	91,621	137,462	-	-	-	229,083	$ 18,769
May	-	-	-	49,055	51,745	143,935	244,734	$ 22,417
June	-	-	-	42,713	45,492	151,728	239,933	$ 21,426
July	-	-	-	49,804	55,071	150,932	255,807	$ 23,351
August	-	-	-	48,618	53,943	155,570	258,132	$ 23,395
September	-	-	-	45,510	48,966	148,835	243,311	$ 21,973
October	-	-	-	49,691	52,653	143,236	245,580	$ 22,550
November	-	94,471	146,096	-	-	-	240,567	$ 19,675
December	-	103,979	141,276	-	-	-	245,255	$ 20,212
Total	-	554,067	827,756	285,392	307,870	894,236	2,869,320	$ 248,355

Demand	WINTER DEMAND (maximum Peak	Partial Peak	Off-Peak	SUMMER DEMAND (maximum Peak	Partial Peak	Off-Peak	Monthly & Yearly	Peak demand charges	Partial peak demand charges	Mothly maximum
January	-	374	374	-	-	-	374	$ -	$ 82	$ 4,783
February	-	381	381	-	-	-	381	$ -	$ 84	$ 4,863
March	-	378	383	-	-	-	383	$ -	$ 83	$ 4,895
April	-	387	387	-	-	-	387	$ -	$ 85	$ 4,944
May	-	-	-	389	389	389	389	$ 6,334	$ 1,472	$ 4,976
June	-	-	-	395	401	401	401	$ 6,432	$ 1,514	$ 5,120
July	-	-	-	411	411	411	411	$ 6,681	$ 1,552	$ 5,248
August	-	-	-	416	415	416	416	$ 6,763	$ 1,570	$ 5,312
September	-	-	-	407	407	412	412	$ 6,620	$ 1,538	$ 5,260
October	-	-	-	398	398	398	398	$ 6,477	$ 1,505	$ 5,088
November	-	416	409	-	-	-	416	$ -	$ 91	$ 5,312
December	-	411	410	-	-	-	411	$ -	$ 90	$ 5,248
	Winter Season Ma		416	Summer Season Maximu		416	416	$ 39,308	$ 9,667	$ 61,050

	Baseline $/year	With shaving $/year	Savings $/year
Grid power energy cost	$ 248,373	$ 248,355	$ 18
Peak demand charges	$ 39,875	$ 39,308	$ 568
Partial peak demand charges	$ 9,819	$ 9,667	$ 152
Mothly maximum demand charges	$ 62,291	$ 61,050	$ 1,241
Total	**$ 360,358**	**$ 358,380**	**$ 1,978**



Step 2: Grid expense impact is analyzed

- Annual grid savings are quantified

Cash Flow Analysis

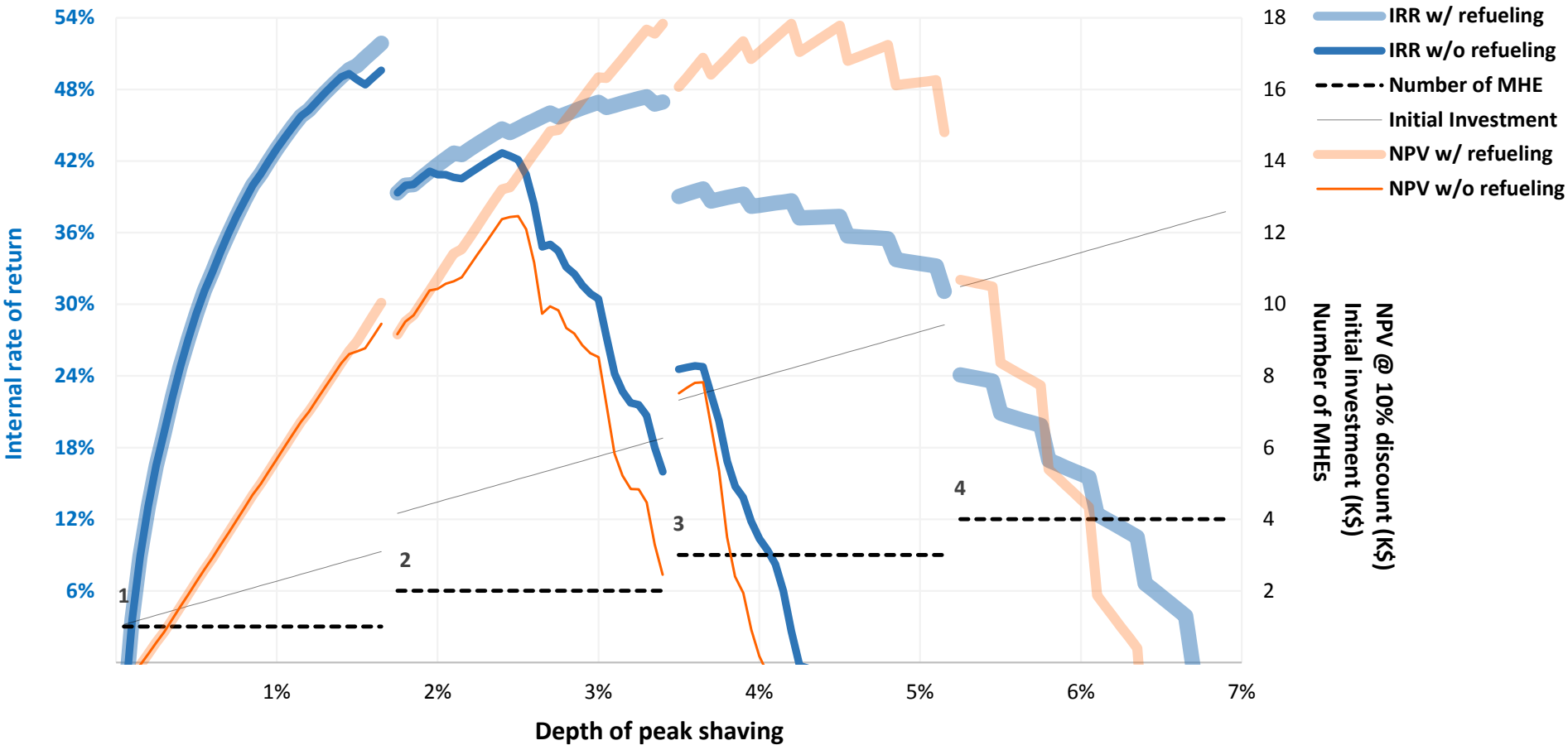
Analysis year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Revenue (avoided costs)																
Grid power energy cost		18.18	18.55	18.92	19.29	19.68	20.07	20.48	20.89	21.30	21.73	22.16	22.61	23.06	23.52	23.99
Peak demand charges		568	579	591	602	614	627	639	652	665	678	692	706	720	734	749
Partial peak demand charges		152	155	158	161	164	167	171	174	178	181	185	188	192	196	200
Mothly maximum demand charges		1,241	1,266	1,291	1,317	1,343	1,370	1,397	1,425	1,454	1,483	1,512	1,543	1,573	1,605	1,637
Total revenue		1,978	2,018	2,058	2,099	2,141	2,184	2,228	2,272	2,318	2,364	2,411	2,459	2,509	2,559	2,610
Operating expenses																
Cost of hydrogen		117	119	122	124	127	129	132	134	137	140	143	145	148	151	154
FC Depreciation		85	85	85	85	85	85	85	85	85	85	85	85	85	85	85
Total expenses		202	204	206	209	211	214	216	219	222	225	227	230	233	236	239
Capital expenditure																
Power electronics cost	2,545															
Installation cost	2,000															
Total expenses	4,545	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Net cash flow	(4,545)	1,776	1,814	1,851	1,890	1,930	1,970	2,011	2,053	2,096	2,139	2,184	2,229	2,276	2,323	2,371

NPV	10,578
IRR	40.9%

Step 3: Financial performance is analyzed

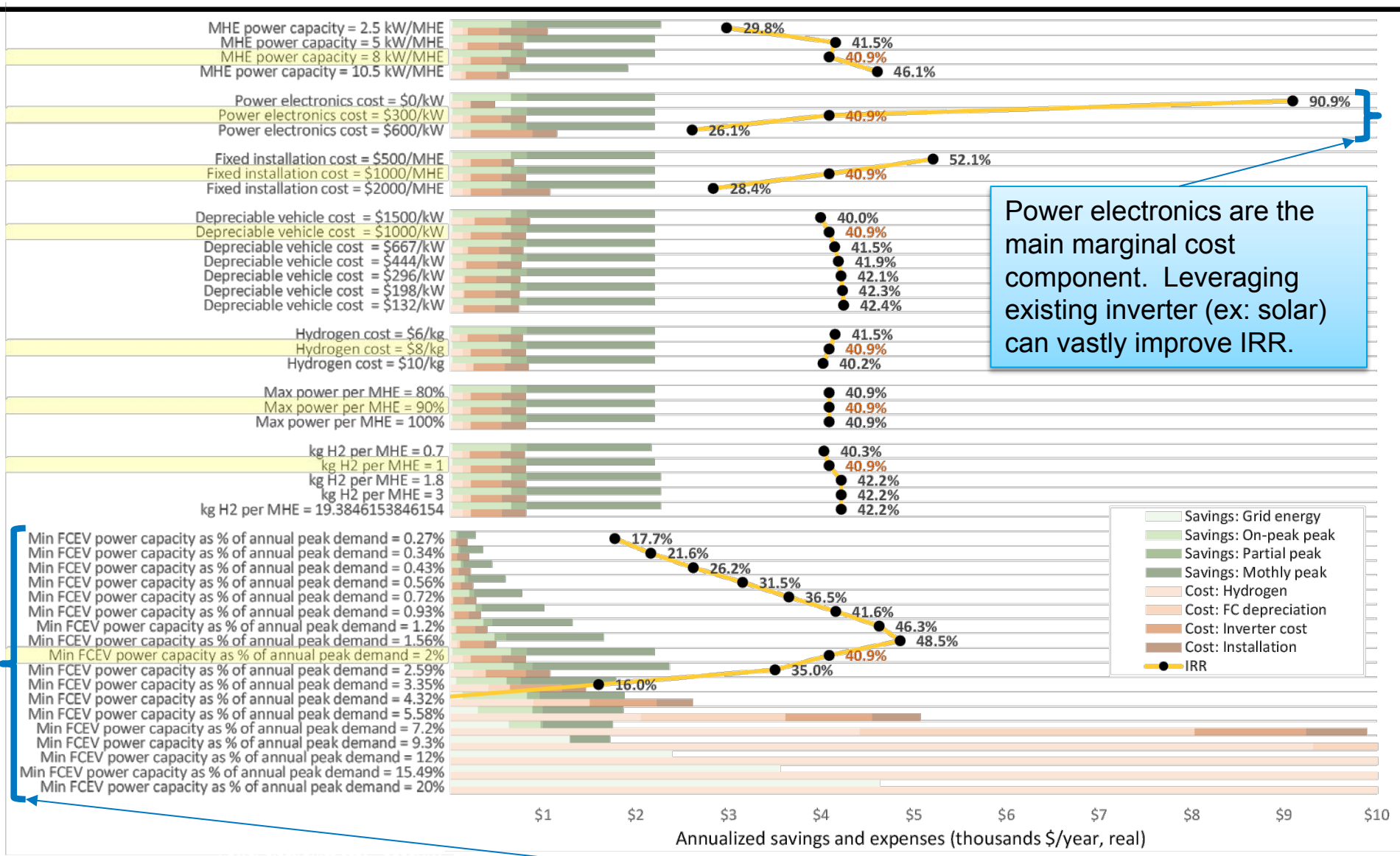
- Internal rate of return (IRR) and net present value (NPV) are used for benchmarking
- NPV is calculated based on 10% discount rate
- All prices are escalated by 2.0% annually (electricity rates, H_2 prices)

Relationship to Peak Shaving Depth



- Depth of peak shaving is a balance between IRR and NPV
- Active fueling can increase returns (but requires more handling)

Sensitivity Analysis

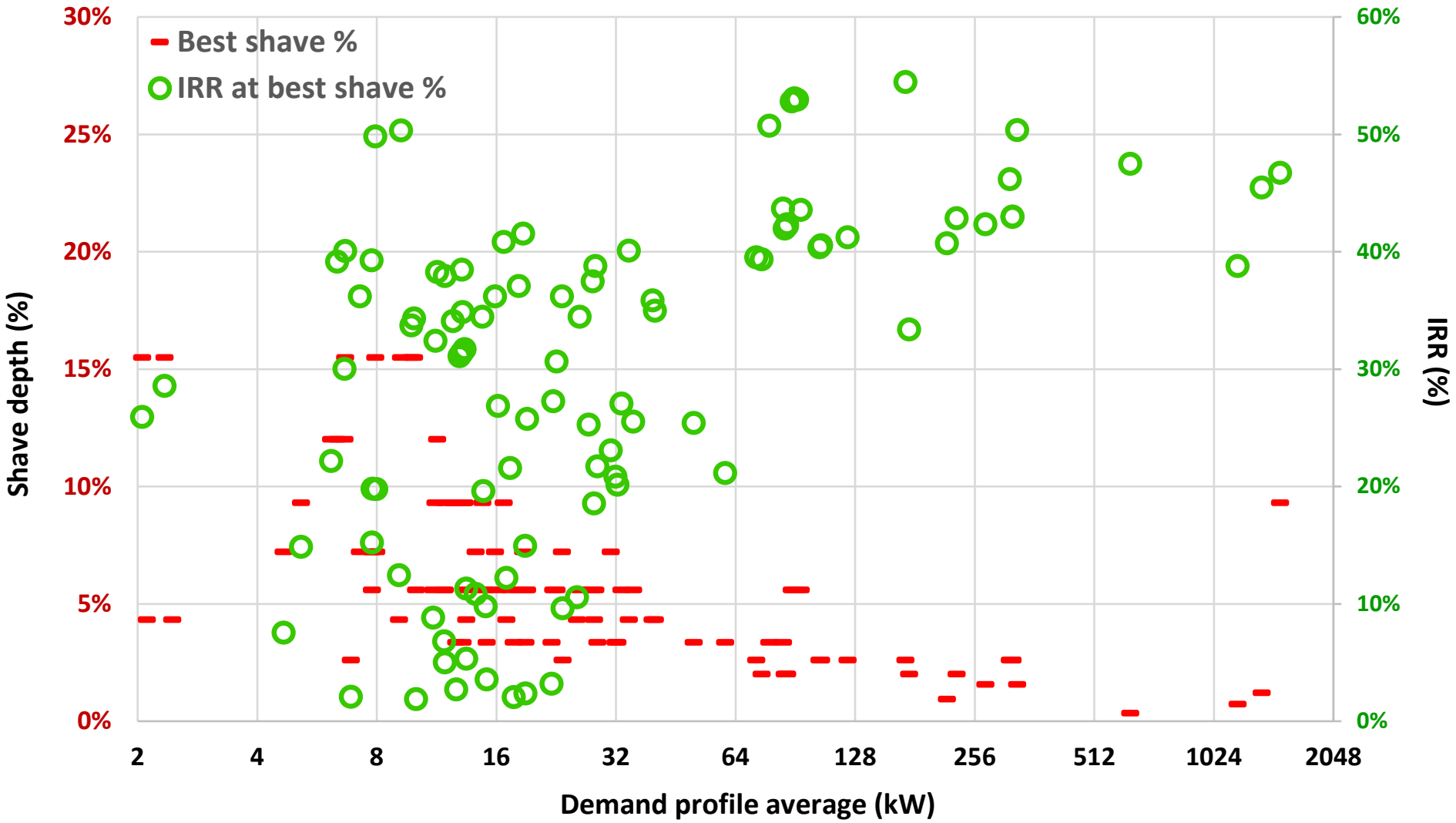


Power electronics are the main marginal cost component. Leveraging existing inverter (ex: solar) can vastly improve IRR.

Performance vs. peak shaving depth exhibits an optimum, in this case, at 2%

Performance vs. Profile Size

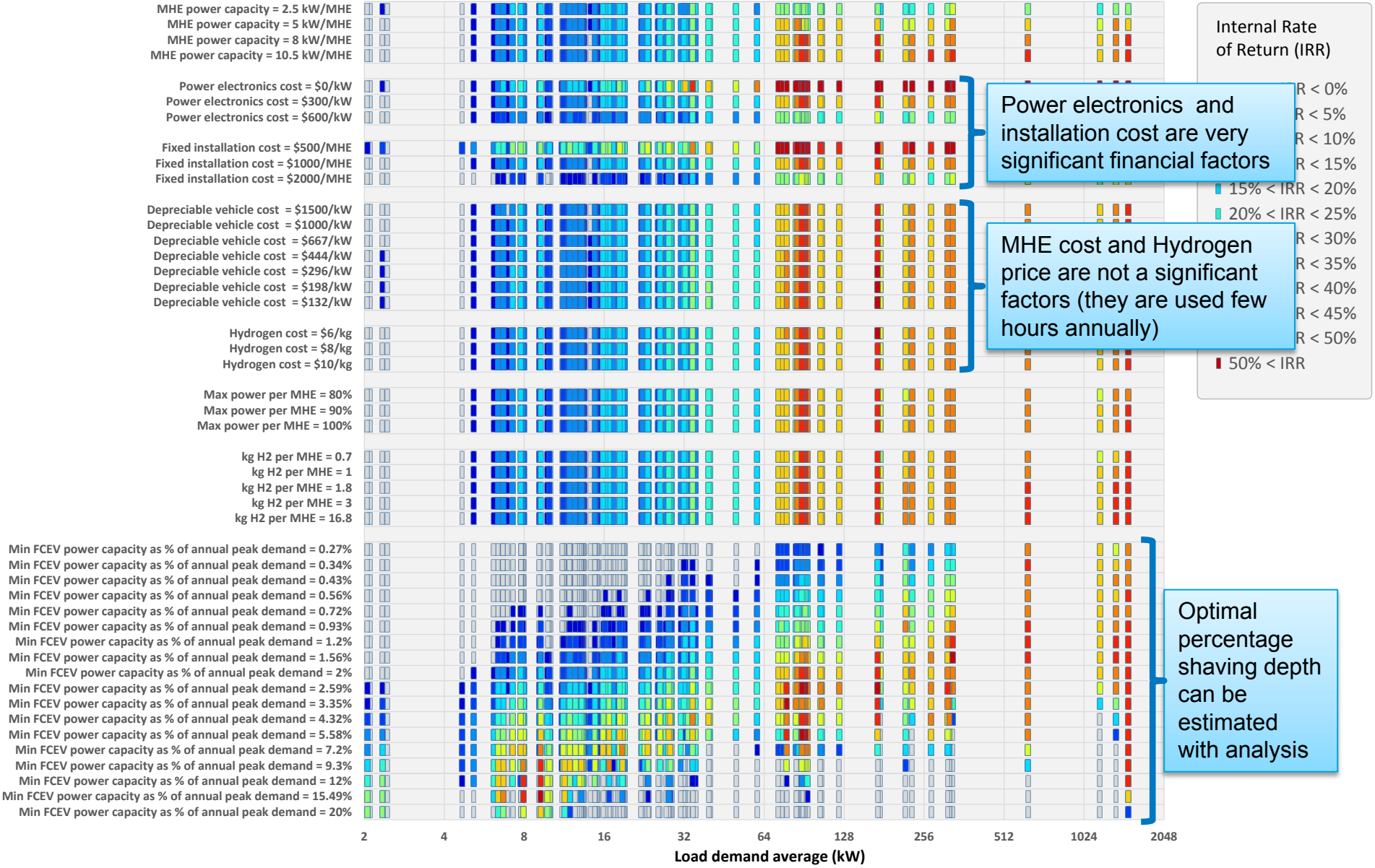
(best depth of peak shaving used)



Larger load profiles tend to harbor better business case opportunities (IRR and NPV)
Larger load profiles are usually less 'peaky', and tend to have shallower depth of peak shaving optimum

Sensitivity of Peak Shaving vs. Profile Size

(103 profiles commercial profiles)



Competitive Analysis (Gen Set)

Gen Set

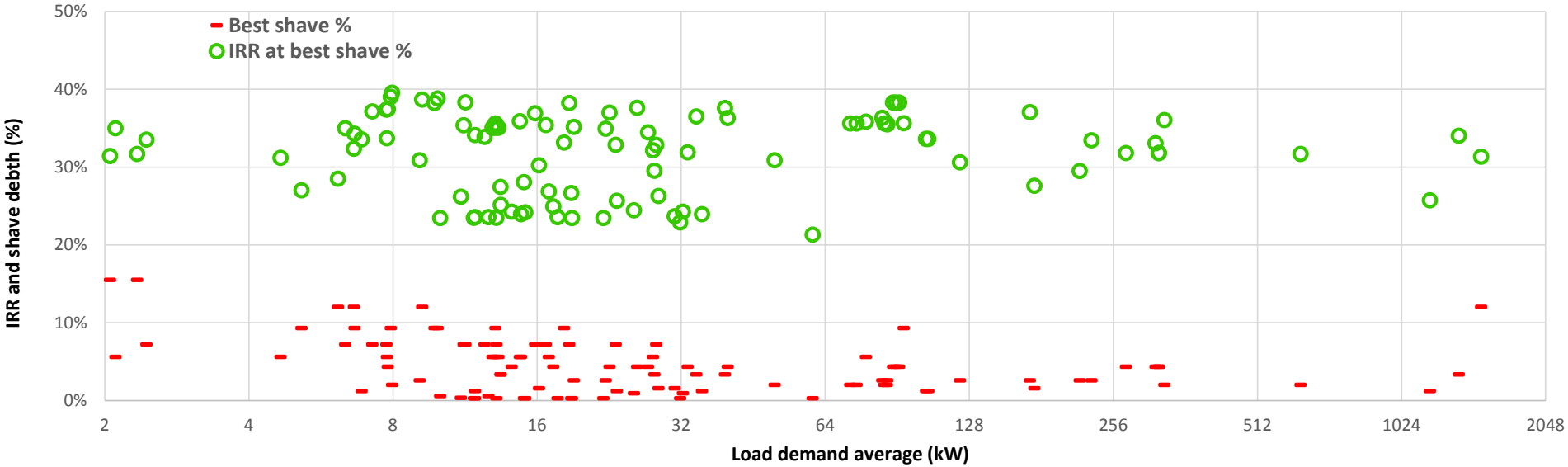
- Installed cost = $670/kW
- Fuel usage = 0.011 mmBTU/kWh
- O&M = 0.02$/h-kW

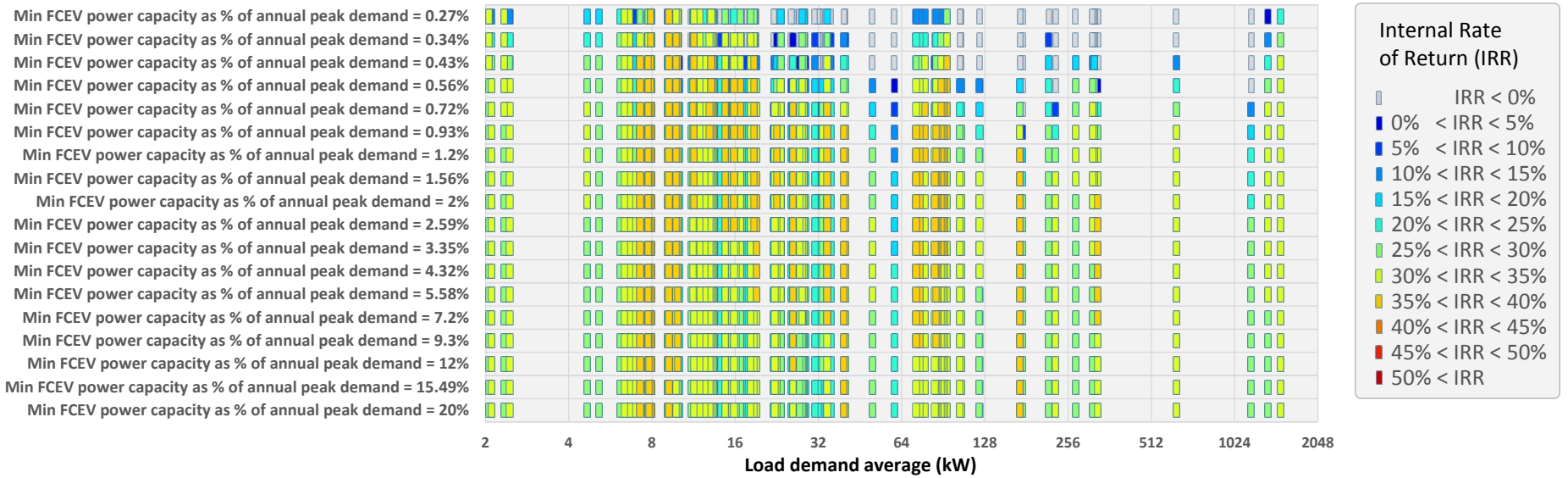
Fuel Costs (EIA)

- Diesel = $3.92/gal
- LPG = $2.61/gal
- Natural gas = $8.13/mmBTU

Above estimates are from recent NREL work for a diesel system at a gov. facility
Assumption: gen sets have the same characteristics for LPG and natural gas

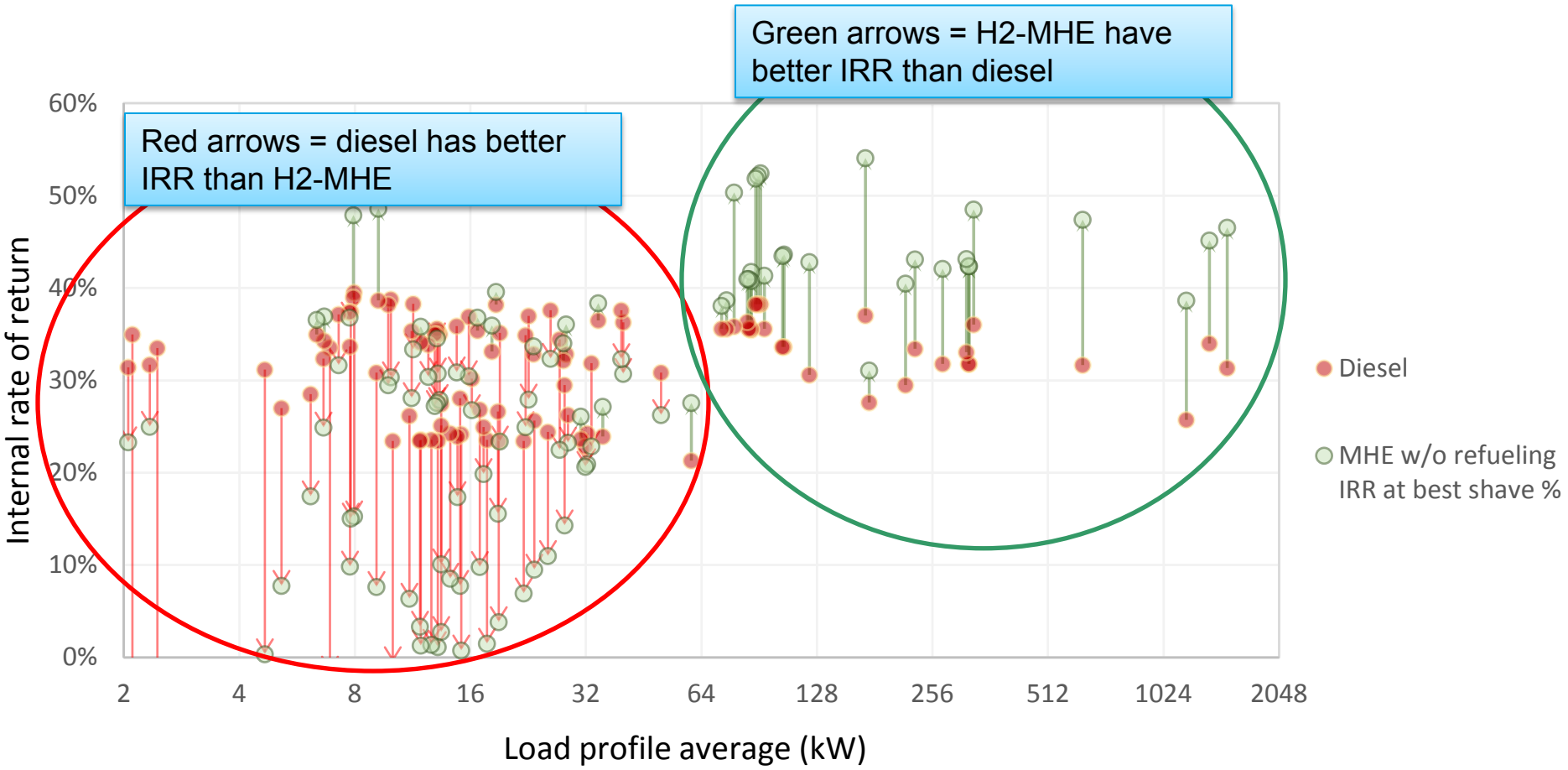
Diesel System IRR





Congruent analysis was performed for diesel generators used for peak shaving.

Comparative Performance vs. Diesel



Hydrogen MHE exhibited better IRR for larger electric loads

- Forklift capital is attributed to material handling operations and only its marginal depreciation factors in IRR
- Diesel capital is attributed only to peak shaving and constitutes higher initial investment

Diesel peak shavers exhibited better IRR for smaller electric loads due to lower installation cost

Discussion & Conclusions

1. MHEs can be effective peak shavers
2. Larger buildings (few hundred kW) are better, and more likely to have TOU rates structures
3. Refueling of peak shaving MHEs throughout the day can help
4. MHEs can compete with combustion – based peak shavers (for load profiles >~60 kW)
5. Effectiveness is highly variable and case-by-case analysis is necessary
6. California has high TOU prices and is a great candidate for peak shaving

Thank You

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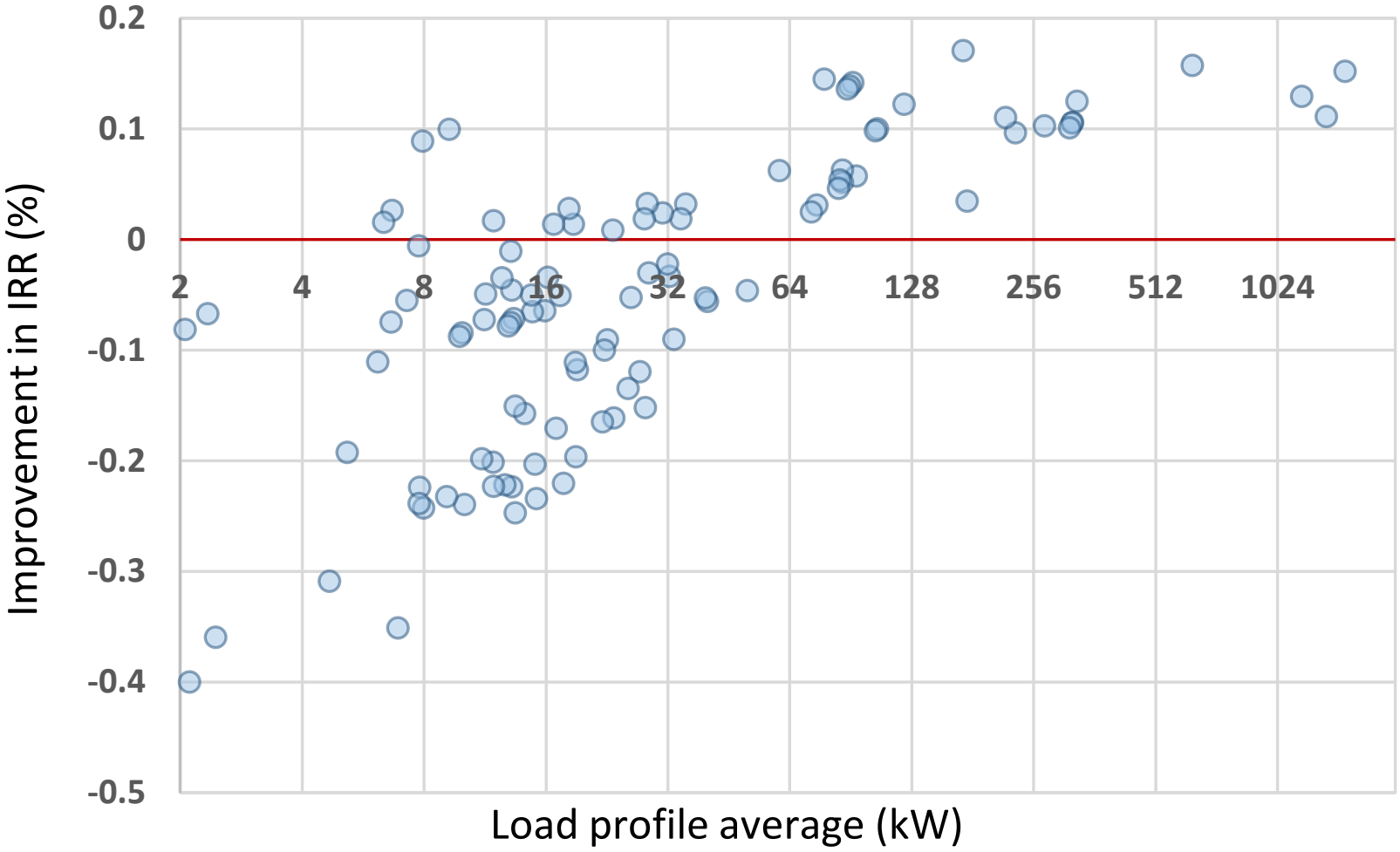
Backup Slides

Practical Considerations

- Use coincides with peak demand
- Drivers don’t necessarily do what you want
- DC/DC can be done
- Class 1 & 2 = 36-48V
- Class 3 = 24V (less desirable)
- Most distribution facilities = Class 2&3
- Class 2 = most likely type

Comparative Performance vs. Diesel

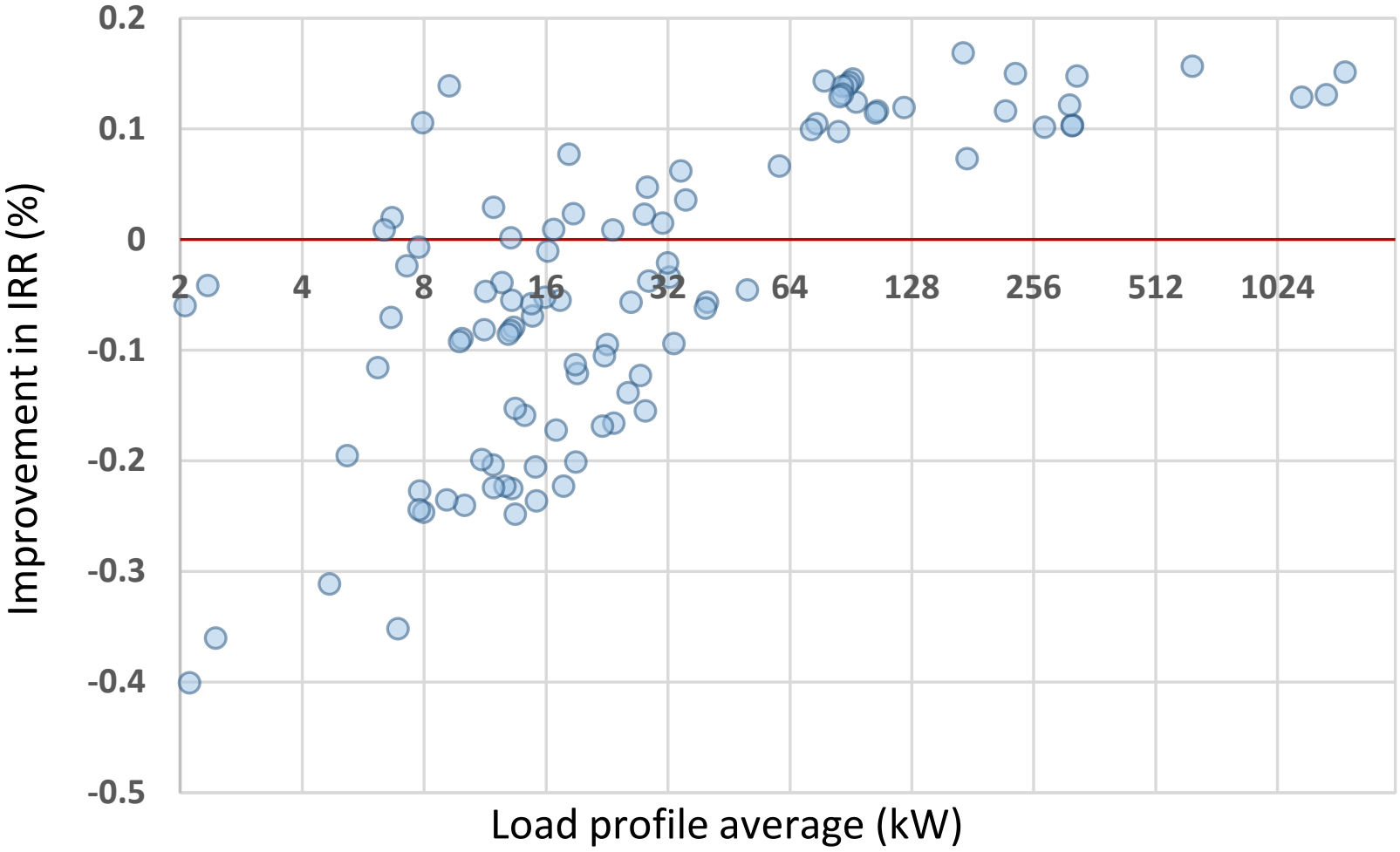
with single fueling per day (w/o multiple refuelings)



Improvement of using MHE without refueling vs. diesel

Comparative Performance vs. Diesel

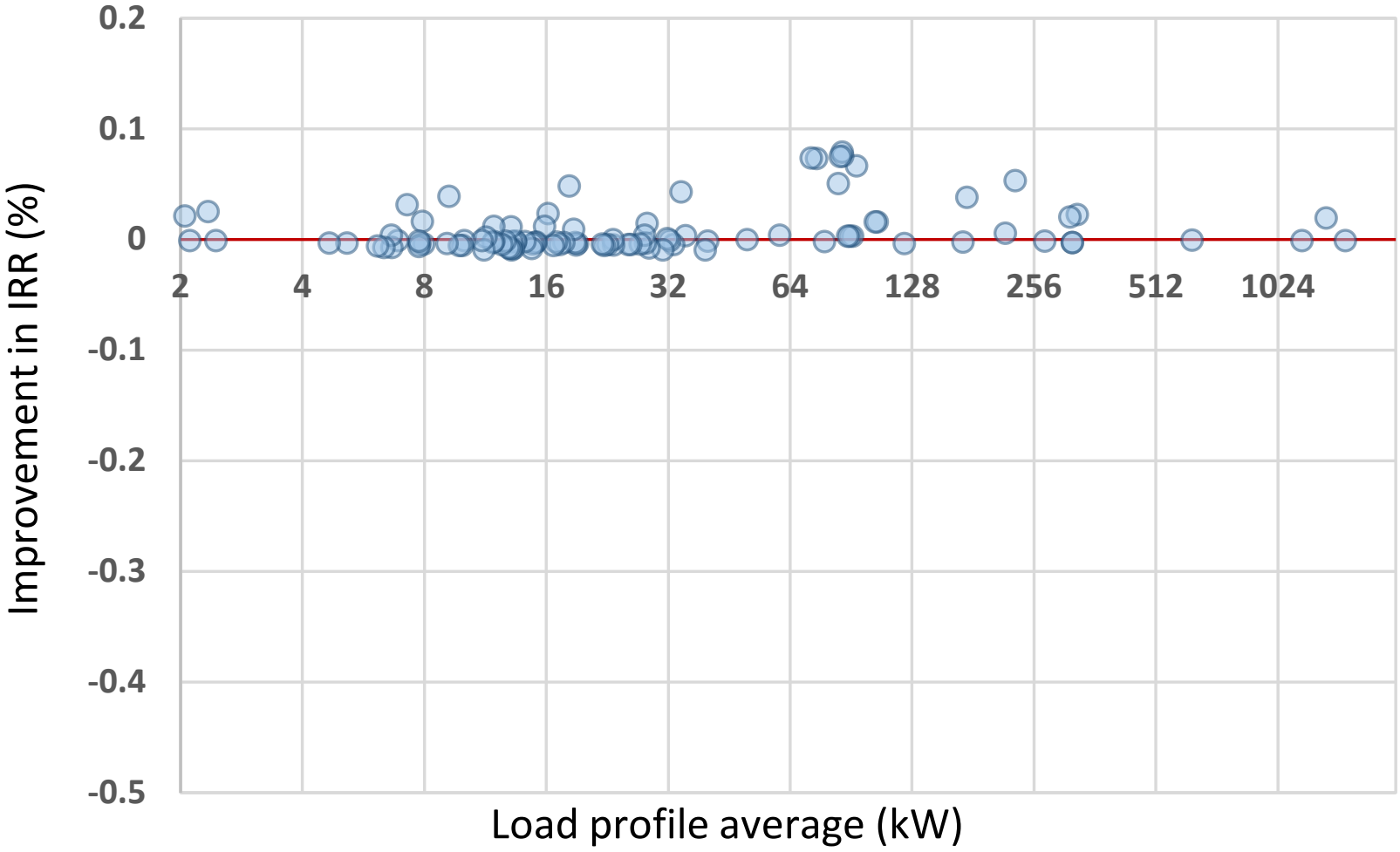
with multiple fueling per day (w/ refuelings as needed)



Improvement of using MHE with multiple refuelings vs. diesel

To Refuel or Not to Refuel?

(one ore multiple refuelings)



IRR of MHE peak shaving with multiple refueling minus single refueling