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Techno-economic Analysis of a High-Temperature Concentrated Solar Power Plant with a Multi-Level Storage System for a Year-Round Guaranteed Dispatchability

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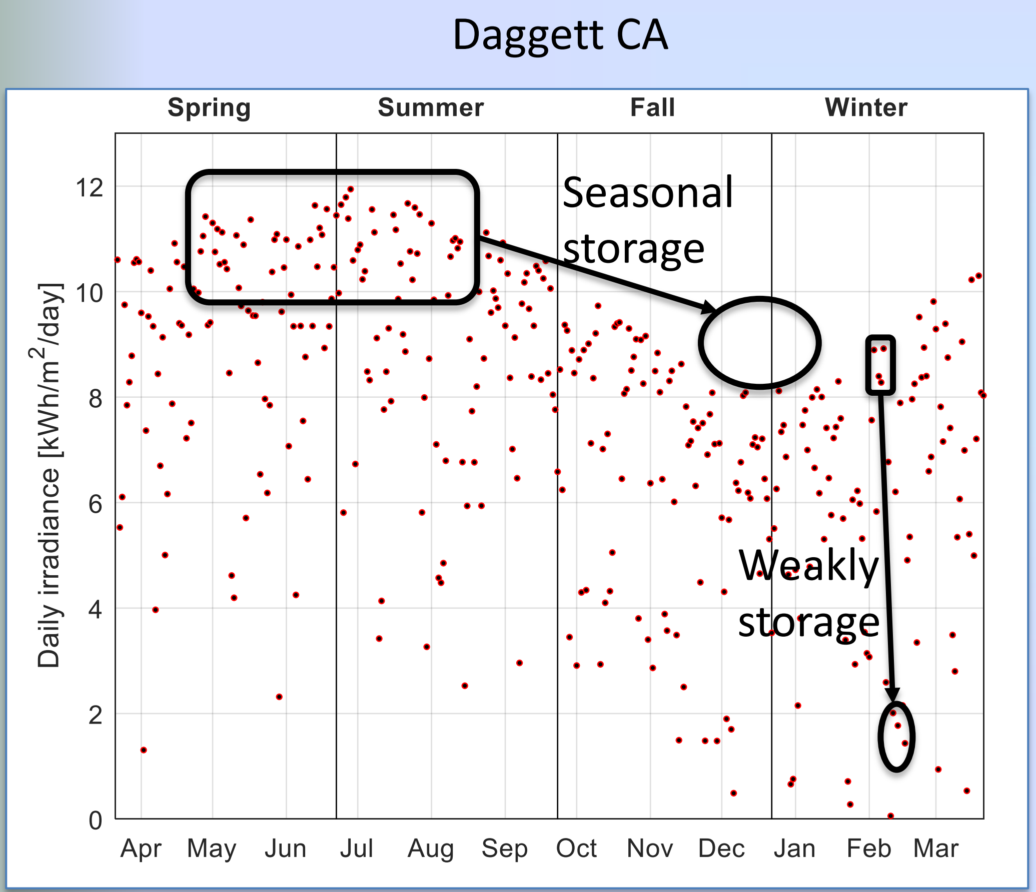
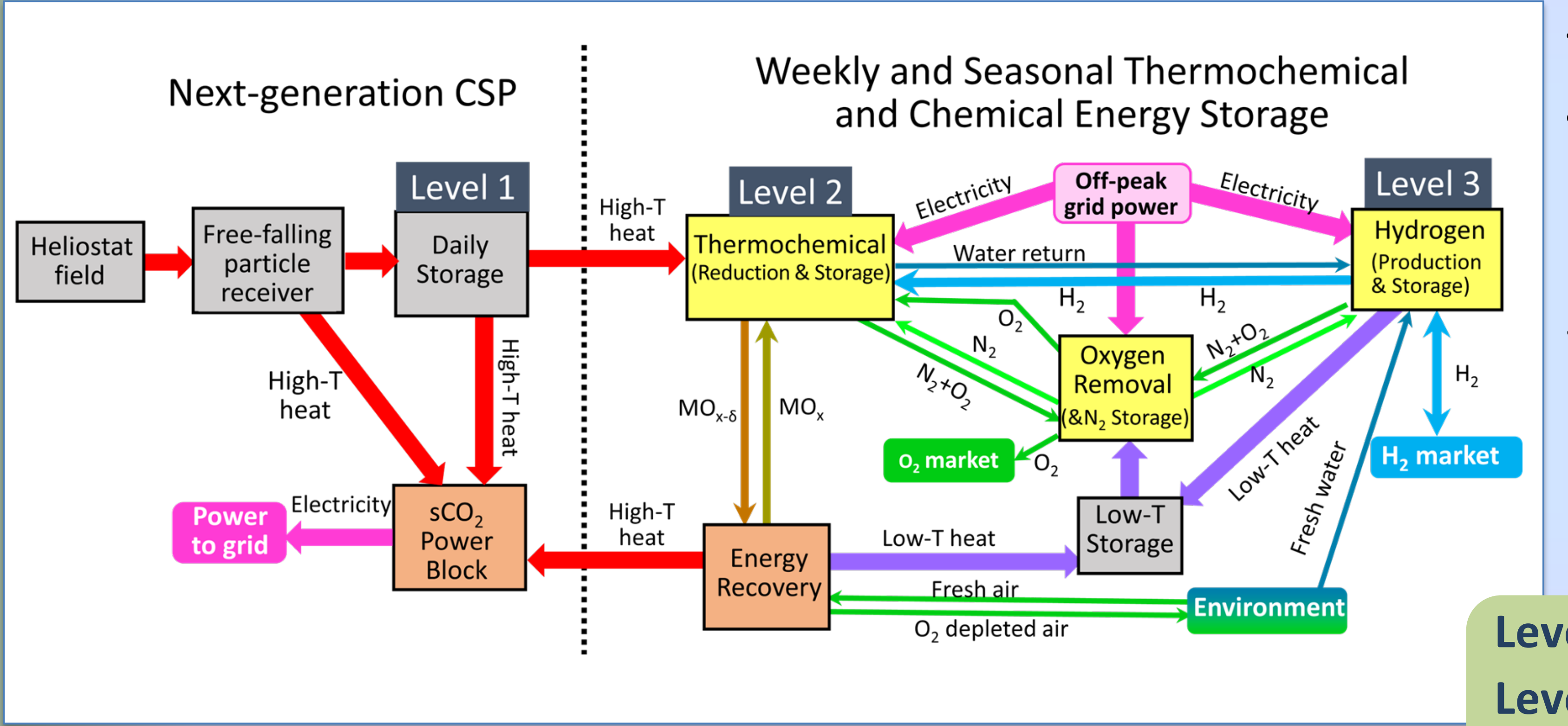
Introduction



Although there are many technologies that cover **short-term** (daily) energy storage to stabilize the grid, only a few covers **medium-term** (weekly) and **long-term** (seasonal) energy storage and are not yet sufficiently developed

Weekly and seasonal storage provides a year-round guaranteed dispatchability

CSP with multi-level storage system

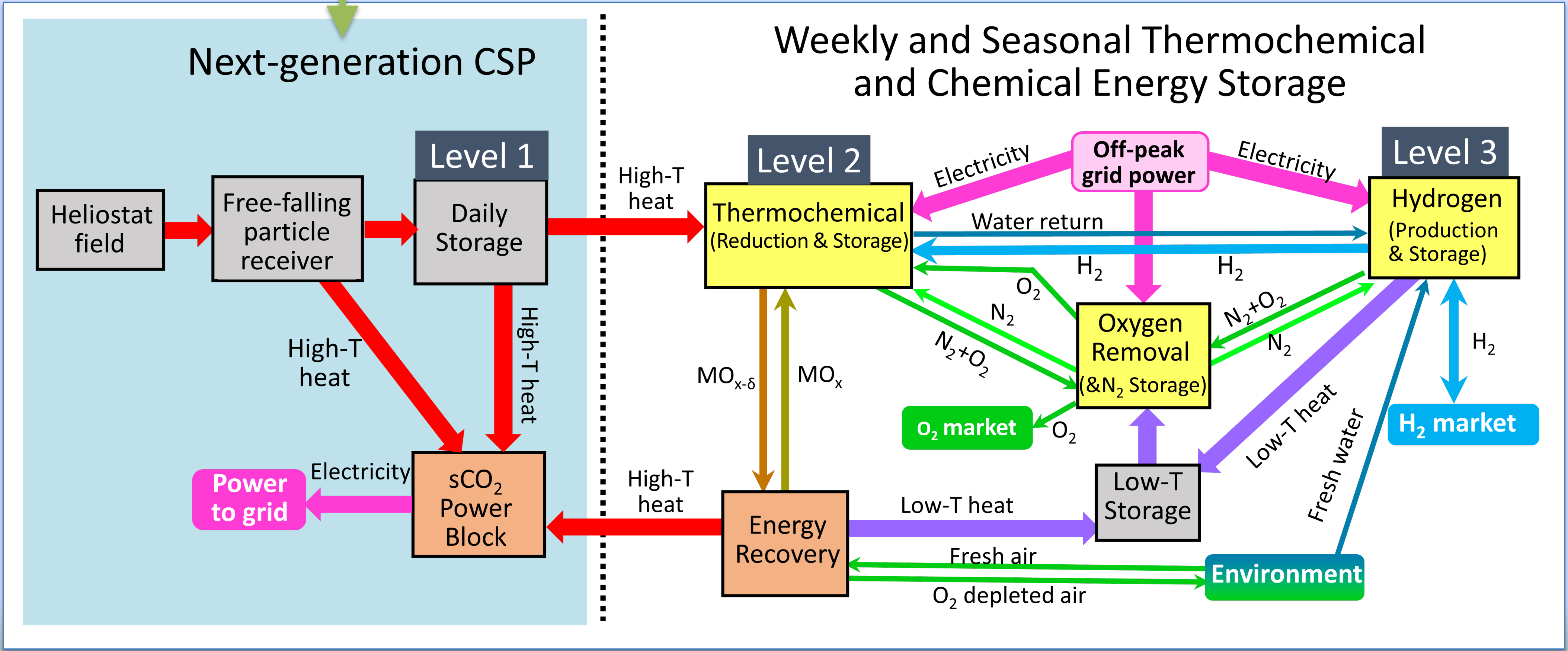


This system offers a **unique flexibility**, where we can **buy and sell electricity** when it is most convenient and is allowed to **sell Hydrogen** as a commodity to offset the operational and capital costs

Level 1 (Daily): Sensible heat
Level 2 (Weekly): Thermochemical heat
Level 3 (Seasonal): Hydrogen

System design: Next-generation CSP

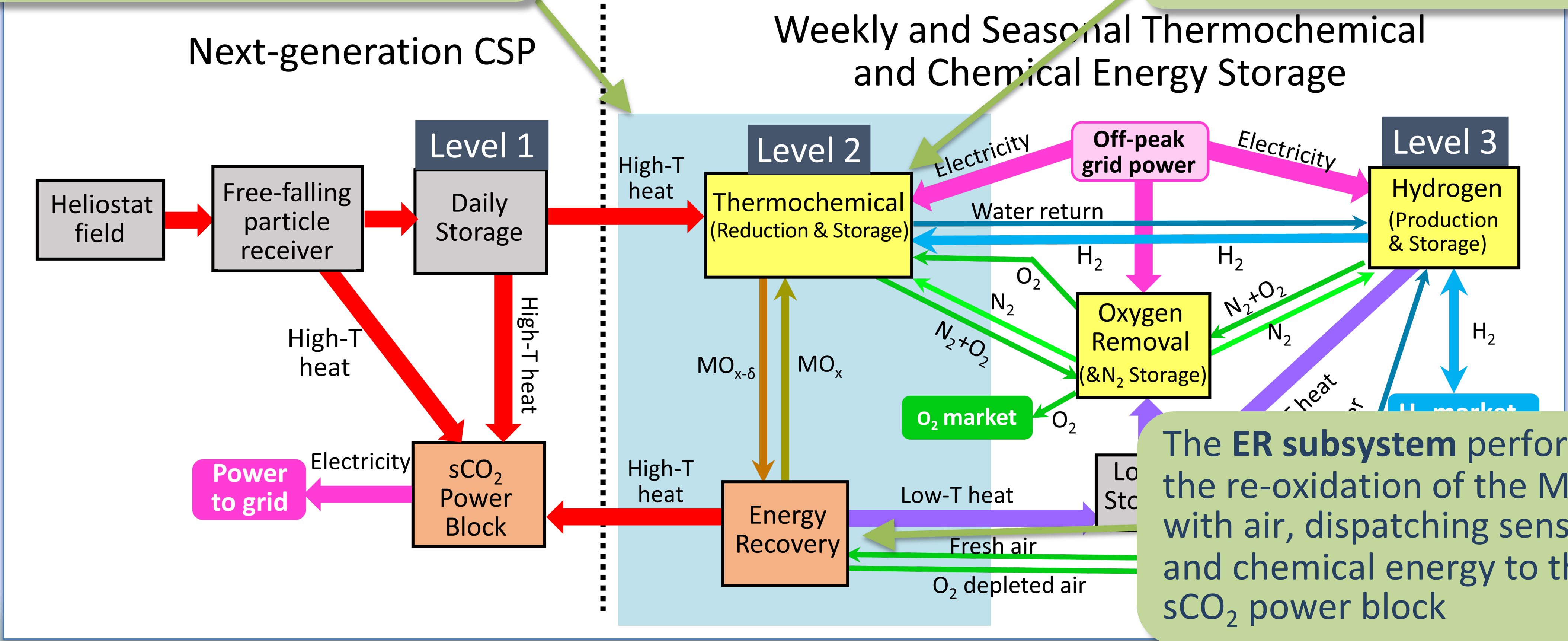
Gen3 plant based: combines a free-falling particle receiver and a supercritical CO_2 power block



System design: Thermochemical energy storage

L2 storage is based on a two-step redox-active metal oxide (MO_x) thermochemical cycle

The **TCES subsystem** performs the thermal reduction of the MO_x in a low oxidation environment

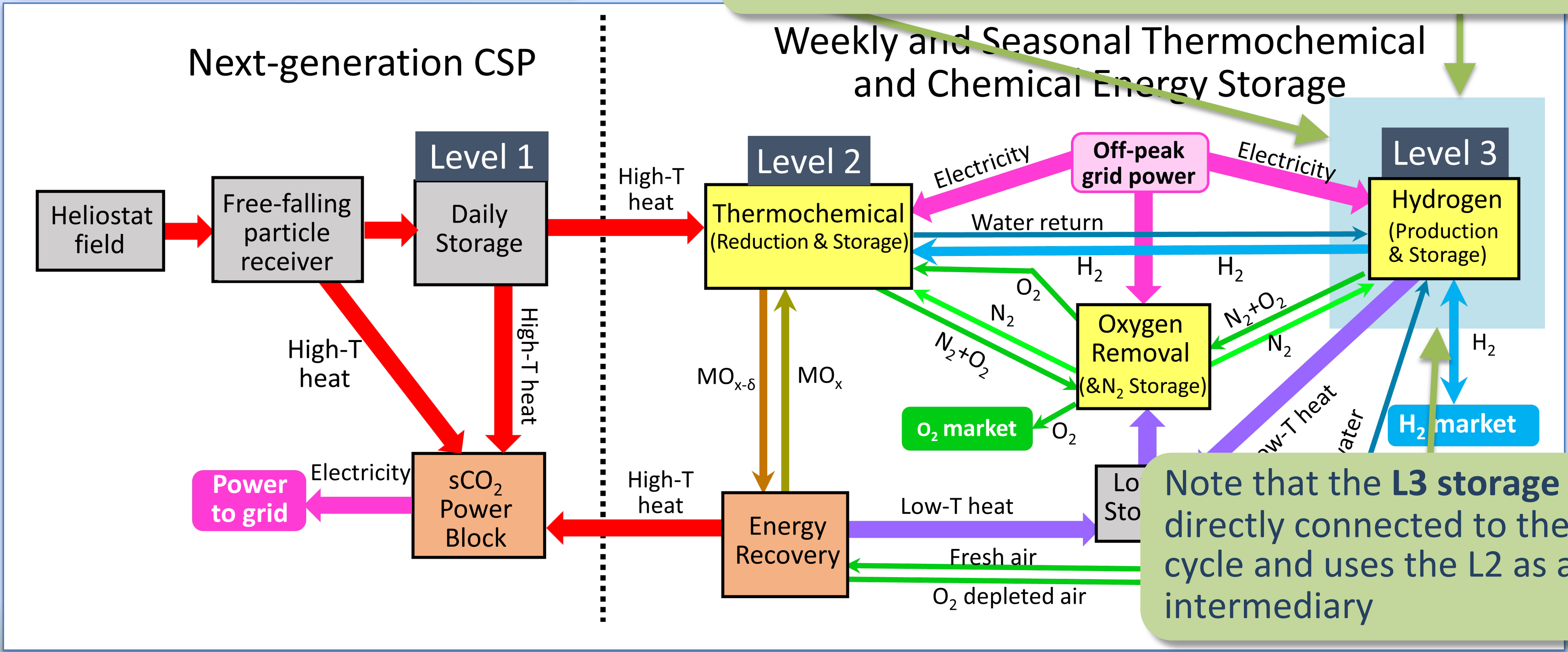


The **ER subsystem** performs the re-oxidation of the MO_x with air, dispatching sensible and chemical energy to the sCO_2 power block

System design: Thermochemical energy storage

L3 storage produces and stores hydrogen with off-peak electricity

It is based on a two-step redox-active MO_x thermochemical cycle whose reactor is designed to work counter-current in both reactions at have an internal solid-solid heat recovery

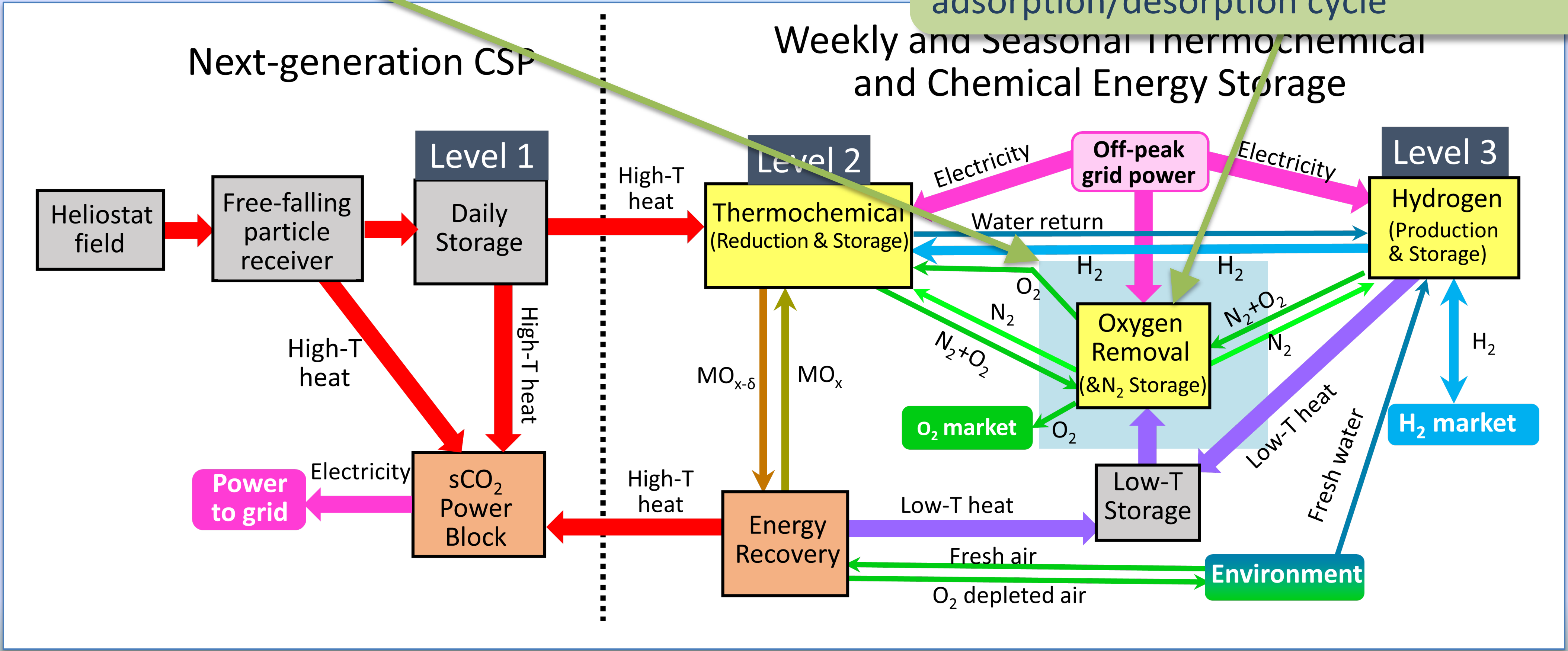


Note that the **L3 storage** is not directly connected to the power cycle and uses the L2 as an intermediary

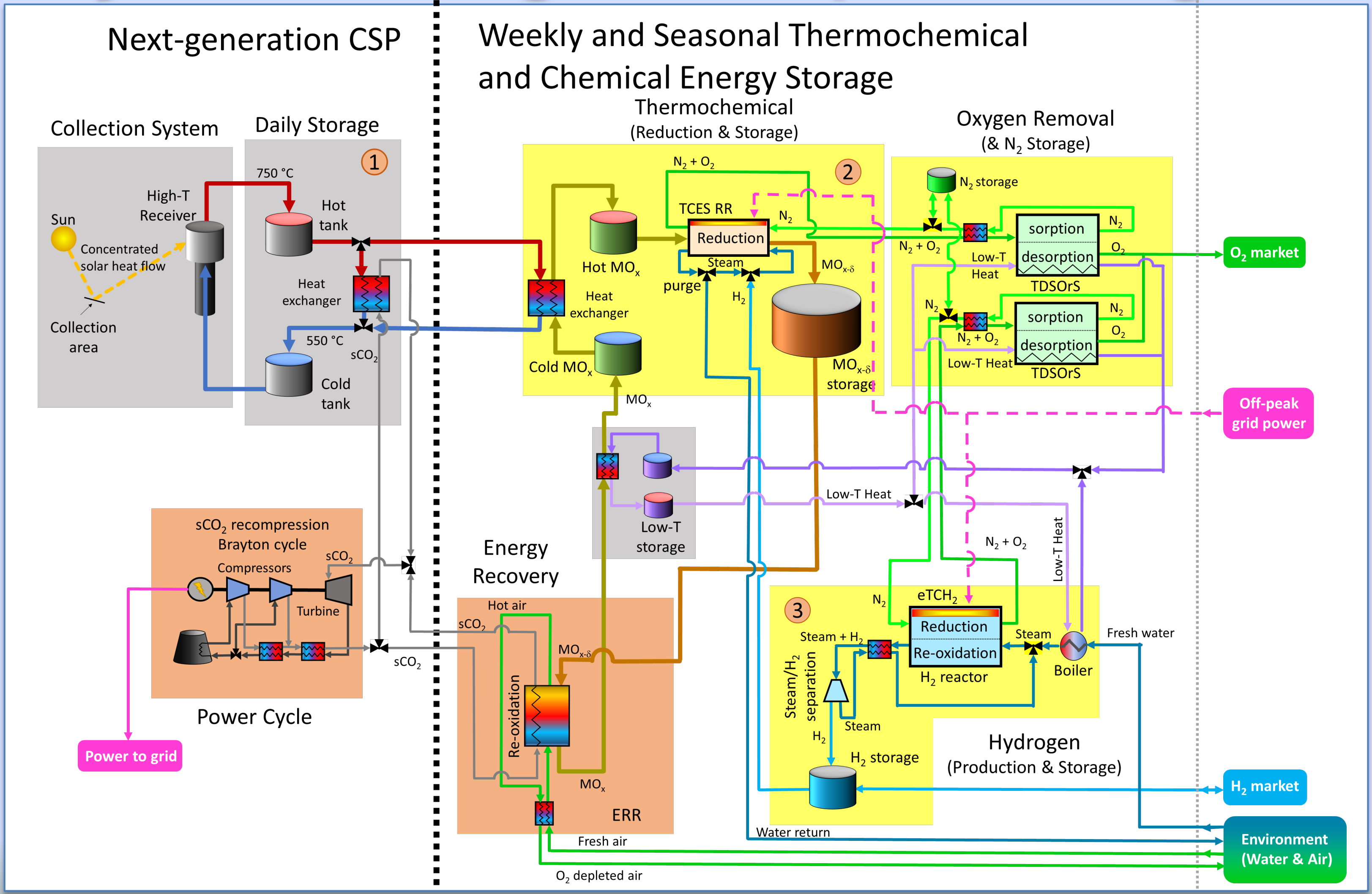
System design: Thermochemical energy storage

Both, **L2** and **L3 storage** systems, require inert gas for its operation

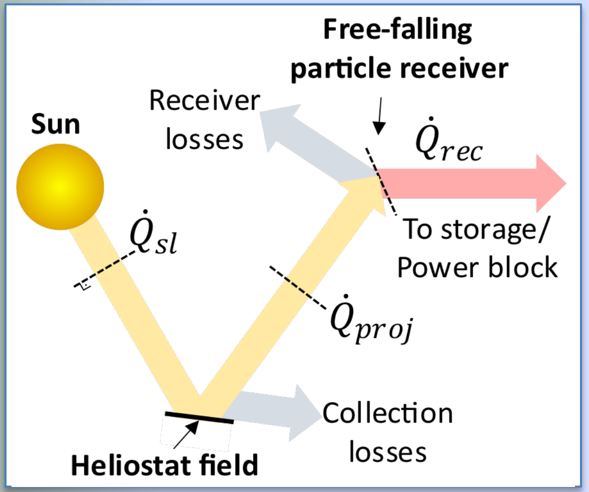
The **O_2 removal subsystem** purified this inert gas based on a two-step adsorption/desorption cycle

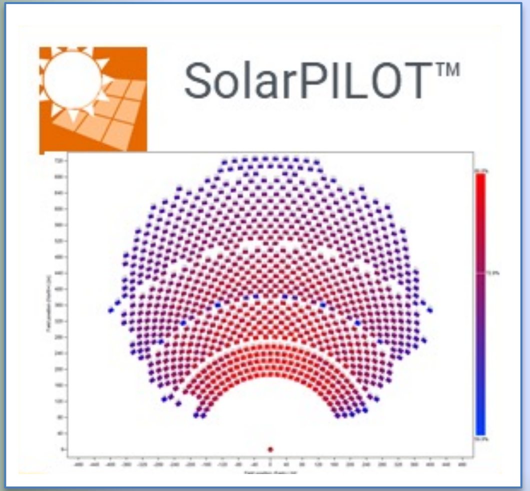


System design: Full plant diagram

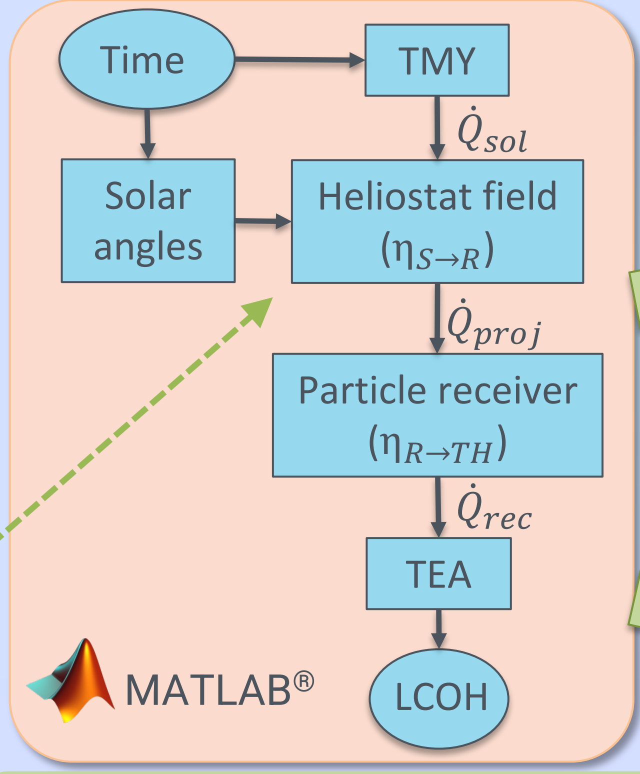


System modeling: next generation CSP

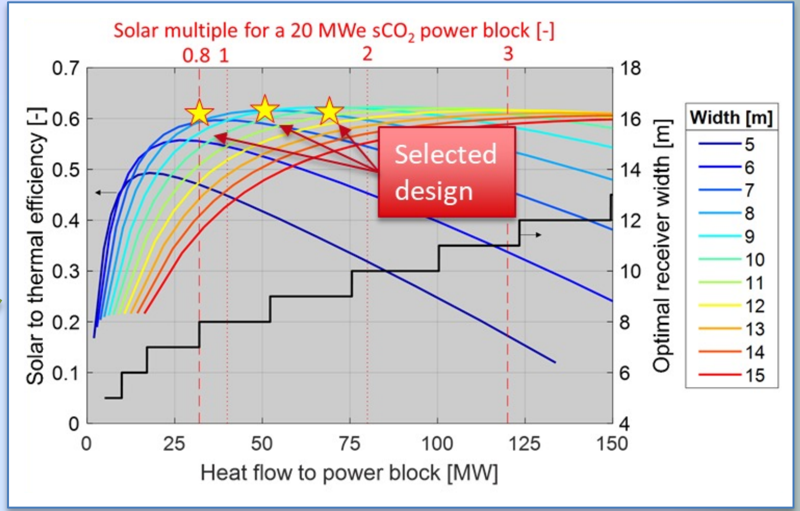




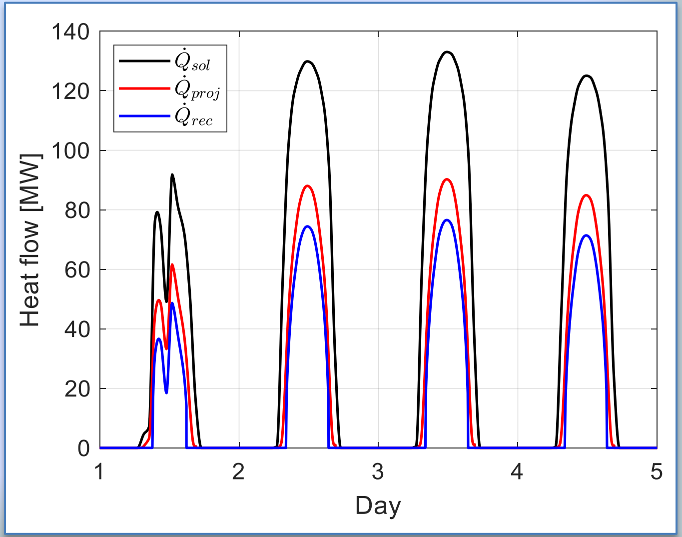
System model



System design

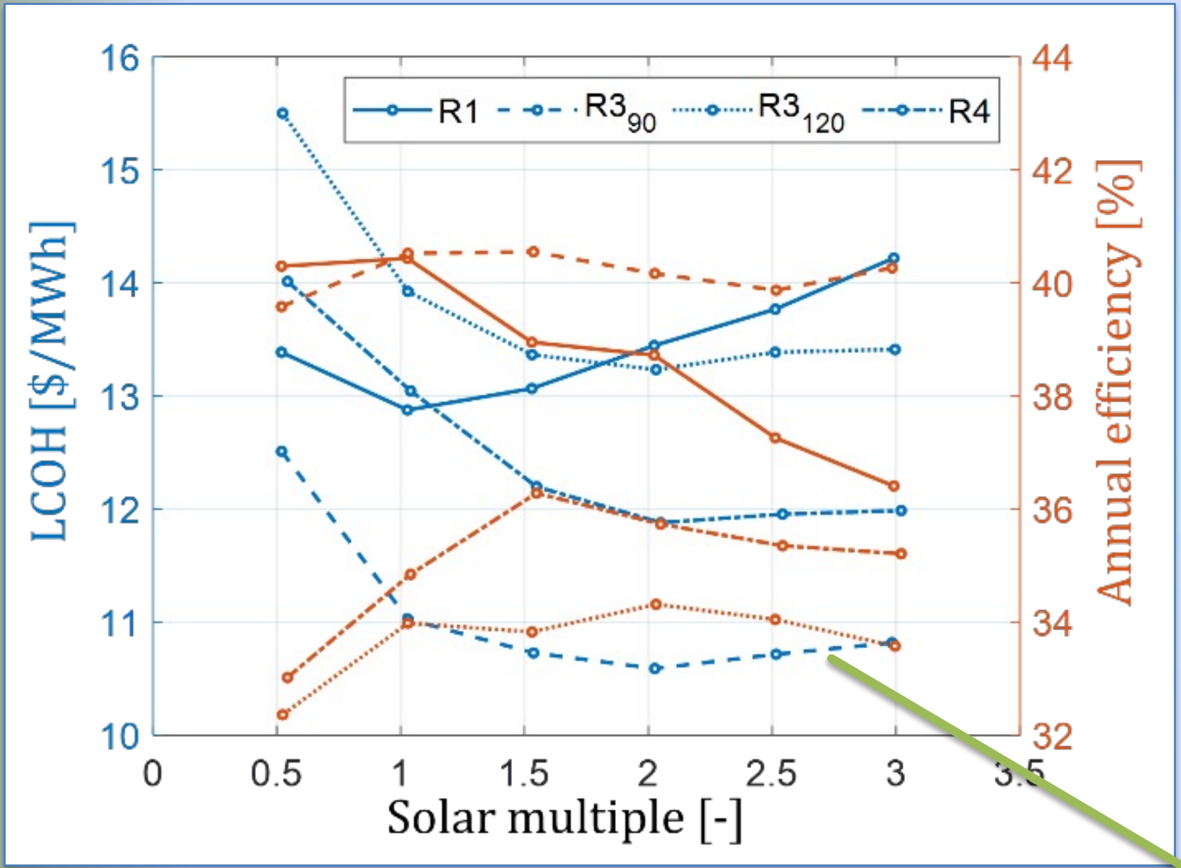


Annual performance

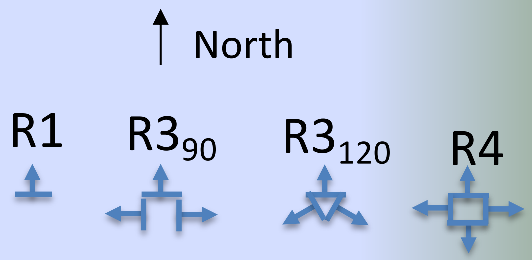


The simulation platform provides a method of quickly and accurately evaluating solar tower systems

Results: next generation CSP



Best solution for each receiver configuration as function of solar multiple: LCOH and annual efficiency (Daggett CA)



Design parameters

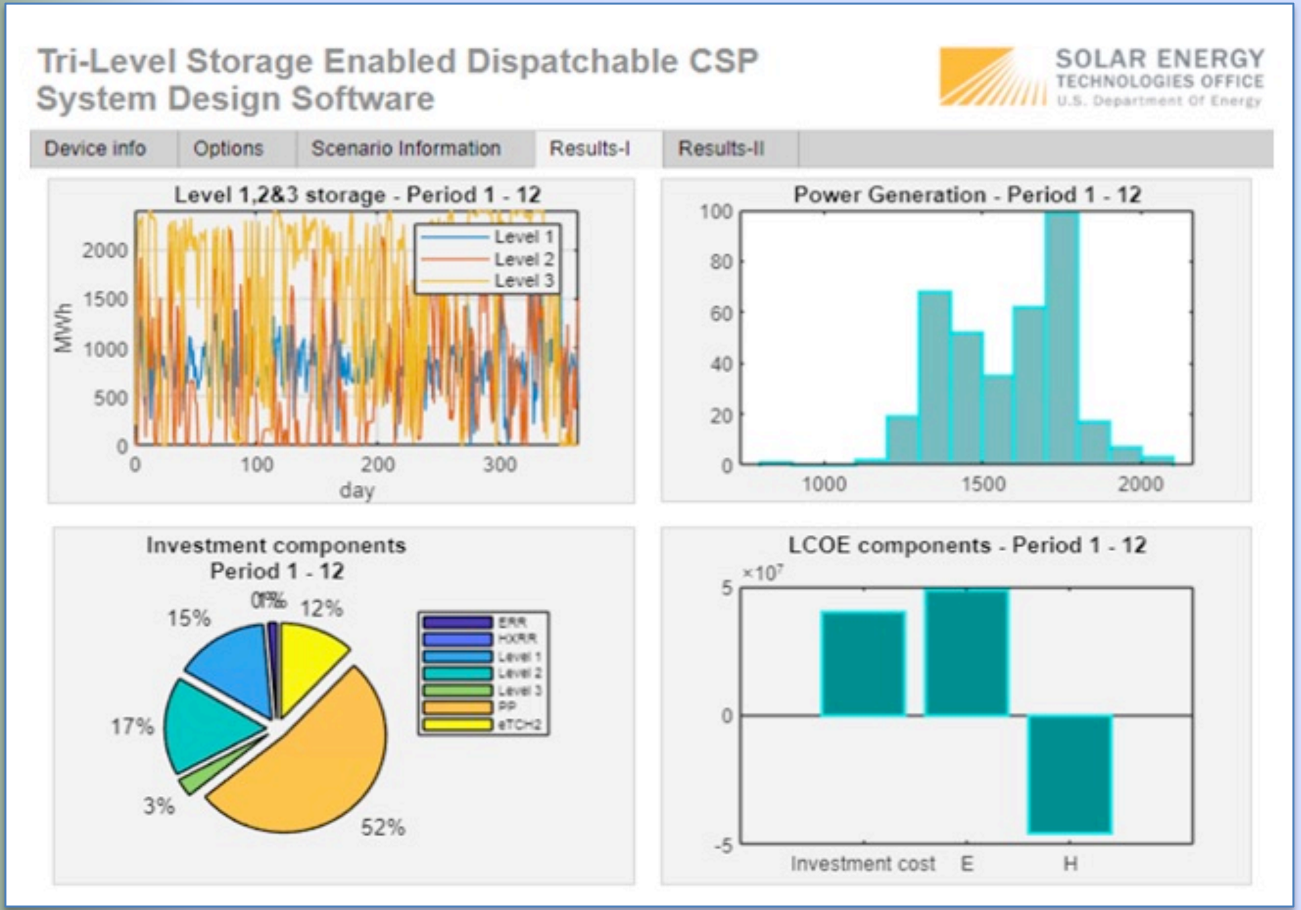
- Receiver configuration
- Receiver width (5-30 m step 1 m)
- Tower height (100-400 m step 5 m)

Optimization

- Optimization algorithm: *surrogateopt*
- Objective function: cost-heat flow ratio

$R3_{90}$ exhibits the lowest LCOH for all the SMs assessed, LCOH ~$11/MWh between SM: 1-3

System modeling: multi-level energy storage



- User friendly simulation platform to simulate multi-level energy storage systems
- It is constructed using mixed-integer linear programming (MILP) formulation
- Includes constraints and objective functions
- Uses reduced order models and cost model of each of the subsystems

This tool can calculate the optimal system operation given a scenario to achieve the minimum levelized cost of energy

Results: multi-level energy storage

LCOE ($/MWh) for 100 MWe Nameplate

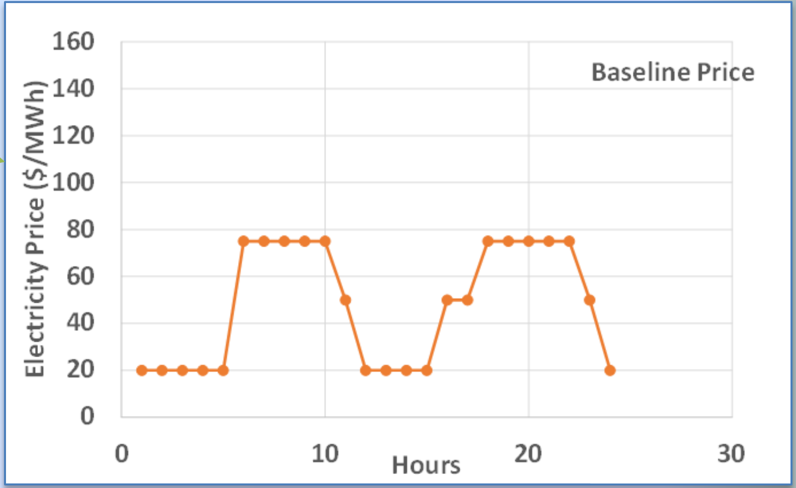
	Solar Multiples										
Level 1 Storage (MWh)	**0.5**	**0.75**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**	**2.5**	**2.75**	**3**
1500 (7.5 hrs)	189.8	137.5	104.8	93.4	80.2	73.9	70.0	68.9	71.7	75.0	77.6
1800 (9 hrs)	193.9	140.3	106.9	95.3	81.8	75.3	70.7	67.9	69.3	71.8	73.8
2000 (10 hrs)	190.8	137.9	105.0	93.9	81.2	75.2	71.0	67.7	68.3	70.1	71.8
2400 (12 hrs)	196.1	141.6	107.6	96.1	83.0	76.7	72.3	68.5	67.9	67.9	68.8
2800 (14 hrs)	201.3	145.2	110.1	98.2	84.7	78.2	73.6	69.7	68.7	67.5	67.5
3200 (16 hrs)	206.6	148.8	112.7	100.4	86.4	79.7	74.9	70.9	69.8	68.1	67.4
3600 (18 hrs)	211.9	152.4	115.2	102.6	88.1	81.1	76.3	72.0	70.8	69.1	68.0
4000 (20 hrs)	217.2	156.0	117.8	104.7	89.9	82.6	77.6	73.2	71.9	70.0	68.9
4400 (22 hrs)	222.5	159.7	120.3	106.9	91.6	84.1	78.9	74.3	72.9	71.0	69.8
4800 (24 hrs)	227.8	163.3	122.8	109.0	93.3	85.6	80.2	75.5	74.0	72.0	70.7

Baseline selected from lowest LCOE at minimum CapEx

Results: multi-level energy storage

Problem: Develop a system design that generates more than the baseline with guaranteed dispatch

- Dynamic electricity pricing model: every day prices can be modified by solar availability, **365 separate cases** possible
- Assumption: At least **6 hours of off-peak** (low-cost) electricity is available every day (likely nights) irrespective of weather
- **10 hours of "guaranteed" generation** under all conditions every day, targeting the highest price hours
- Assumes a **continuous demand for H_2** in the market
- H_2 Price: $60/MWh ($2/kg, based on 120 MJ/kg LHV)
- Does not include revenues from sales of O_2 or capacity payments or other



Results: multi-level energy storage

L1, L2, and L3 systems under study

Case No	L1 MWh (Hours)	SM	L2 MWh (Hours)	RR MW	L3 MWh (Hours)	$eTCH_2$ MW	Weather
1	2000 (10)	2.25					Normal
2	2000 (10)	2.25					Modified
3	2000 (10)	2.25	2200 (10)	367			Normal
4	2000 (10)	2.25	2200 (10)	367			Modified
5	2000 (10)	2.25	2200 (10)	200	2400 (10)	300	Normal
6	2000 (10)	2.25	2200 (10)	200	2400 (10)	300	Modified

Only L1 (cases 1–2)

L1-L2 (cases 3–4)

L1-L2-L3 (cases 5–6)

TMY Daggett CA

Data "modified" by adding 1 week of low insolation (avg. 2 hours of sun/per day) to all months

Level 1, 2 and 3 with similar storage capacity

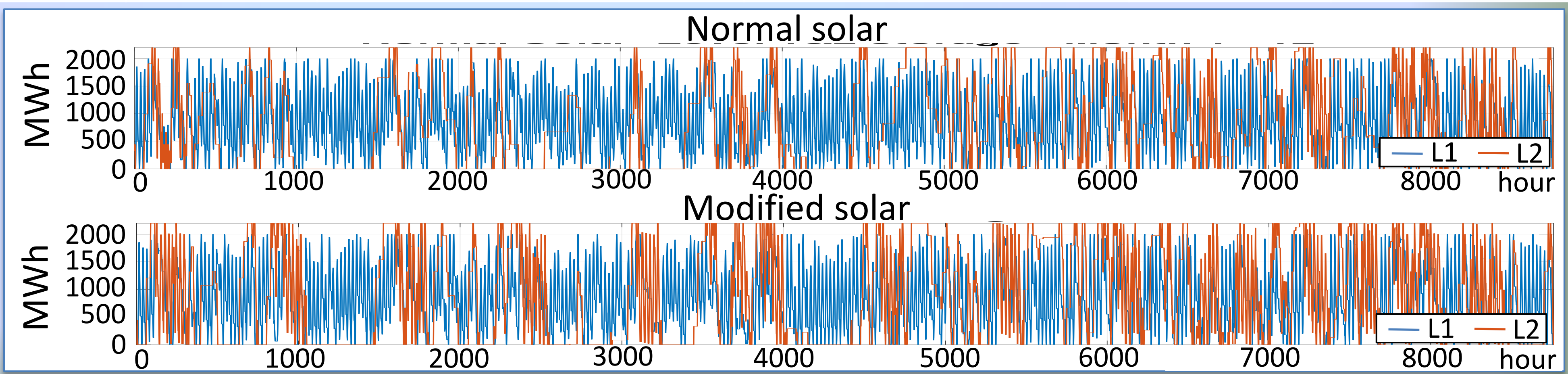
L1-to-electricity: 50%
L2-to-electricity: 45.5%
L3-to-electricity: 41.7%

Results: multi-level energy storage

L1-L2 system

- Generation went up with addition of Level 2 because generation gaps in low insolation periods are filled
- The revenue does not compensate the higher investment cost and operating cost of off-peak electricity

Case No	Annualized Plant Cost	Off-peak Electricity Cost	Hydrogen Revenue	LCOE	Annual Generation	Electricity Revenue	Net Earnings
	$M	$M	$M	S/MWh	% Capacity	$M	$M
1	33.00	0.00		67.83	0.56	48.30	15.30
2	33.00	0.00		79.67	0.47	42.20	9.20
3	36.50	4.22		77.60	0.61	53.90	13.18
4	36.50	8.92		90.40	0.58	55.10	9.68
5	39.90	46.90	56.90	55.91	0.61	53.90	24.00
6	39.90	49.40	54.00	69.10	0.58	55.10	19.80

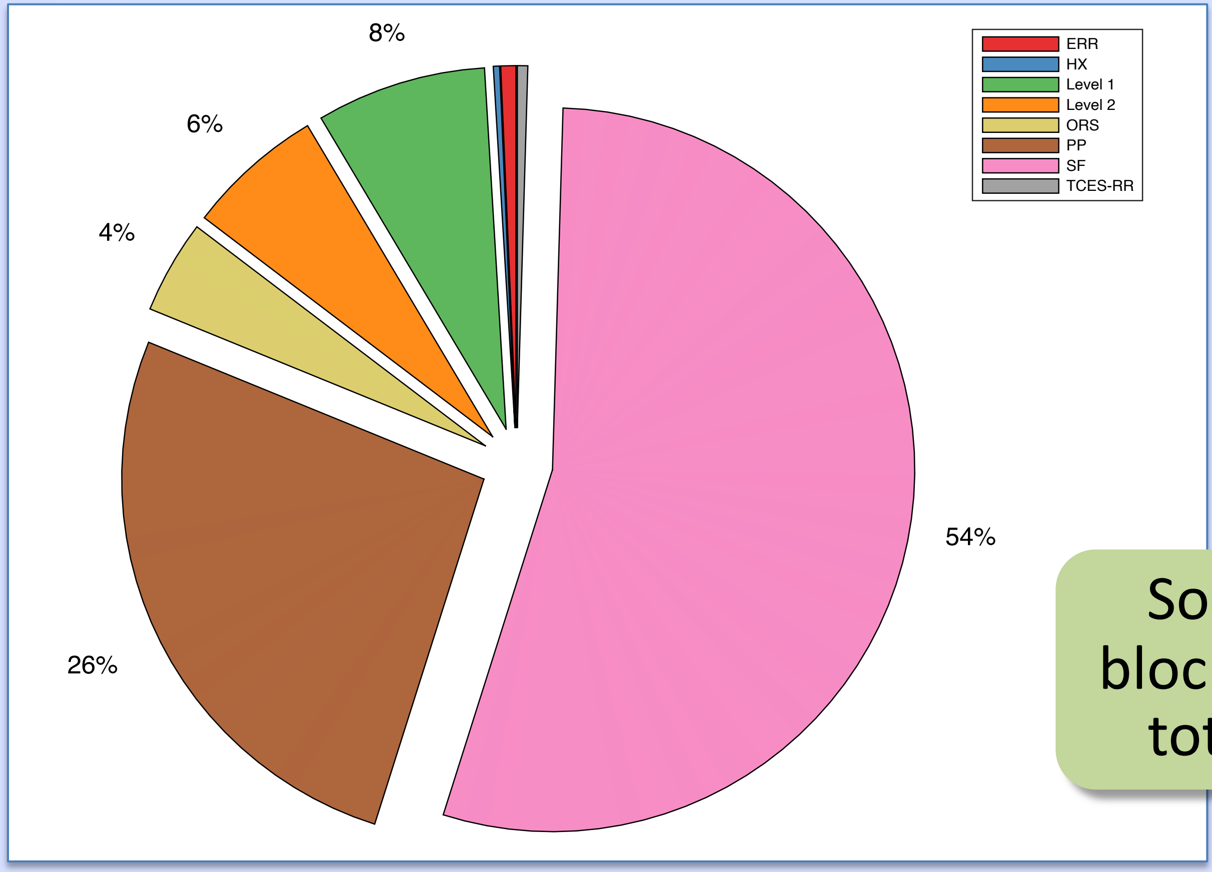


LCOE 15% more than baseline

Results: multi-level energy storage

L1-L2 system

Capital expenses distribution



Solar plant and power block make up 80% of the total investment costs

Results: multi-level energy storage L1-L2-L3 system

- Generation w.r.t. L1-L2 system did not increase significantly because not many additional "profitable" generation hours
- The revenues from the H_2 sell compensates for the higher CapEx and OpEx

LCOE 16% less than baseline

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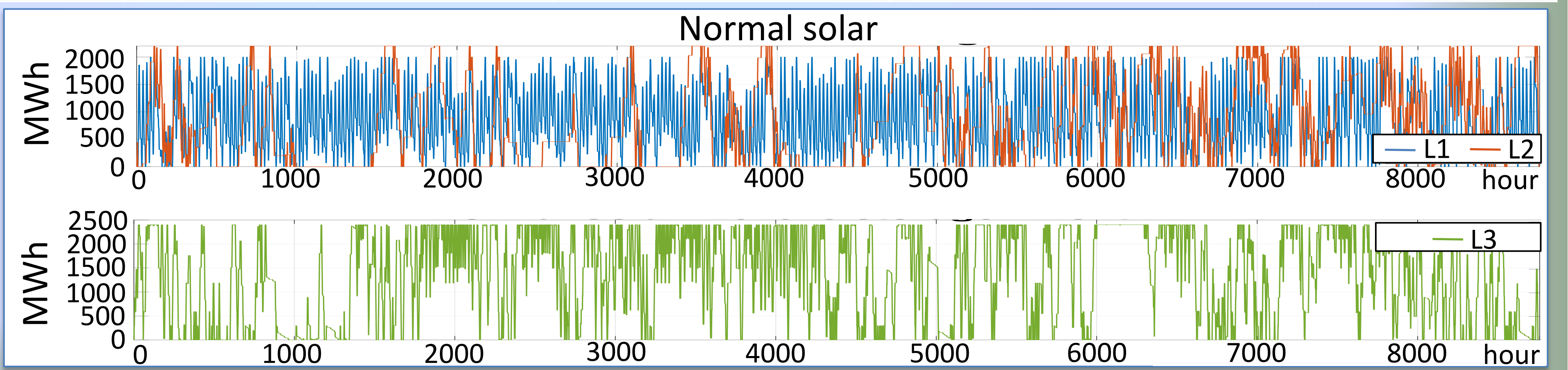

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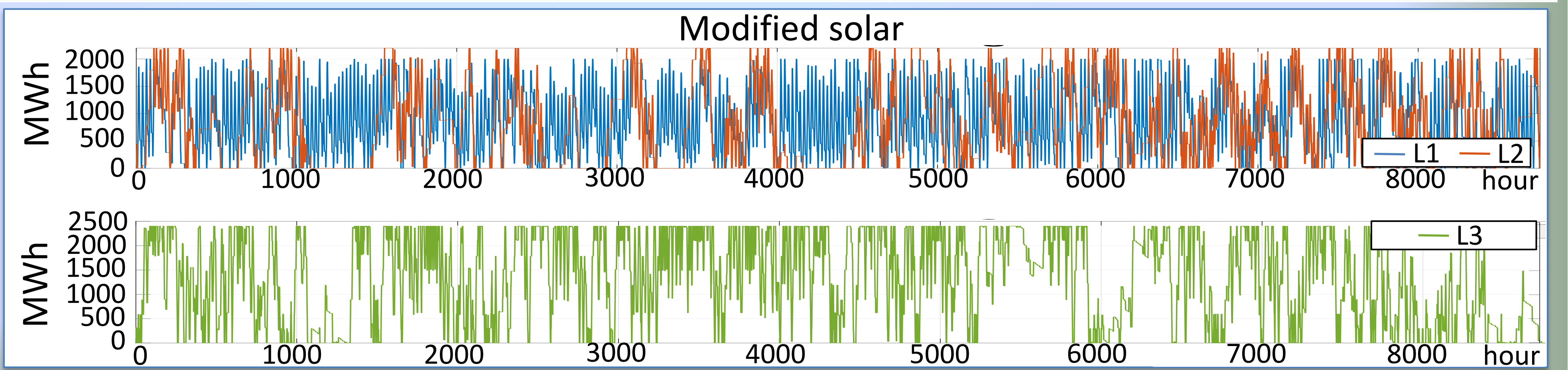
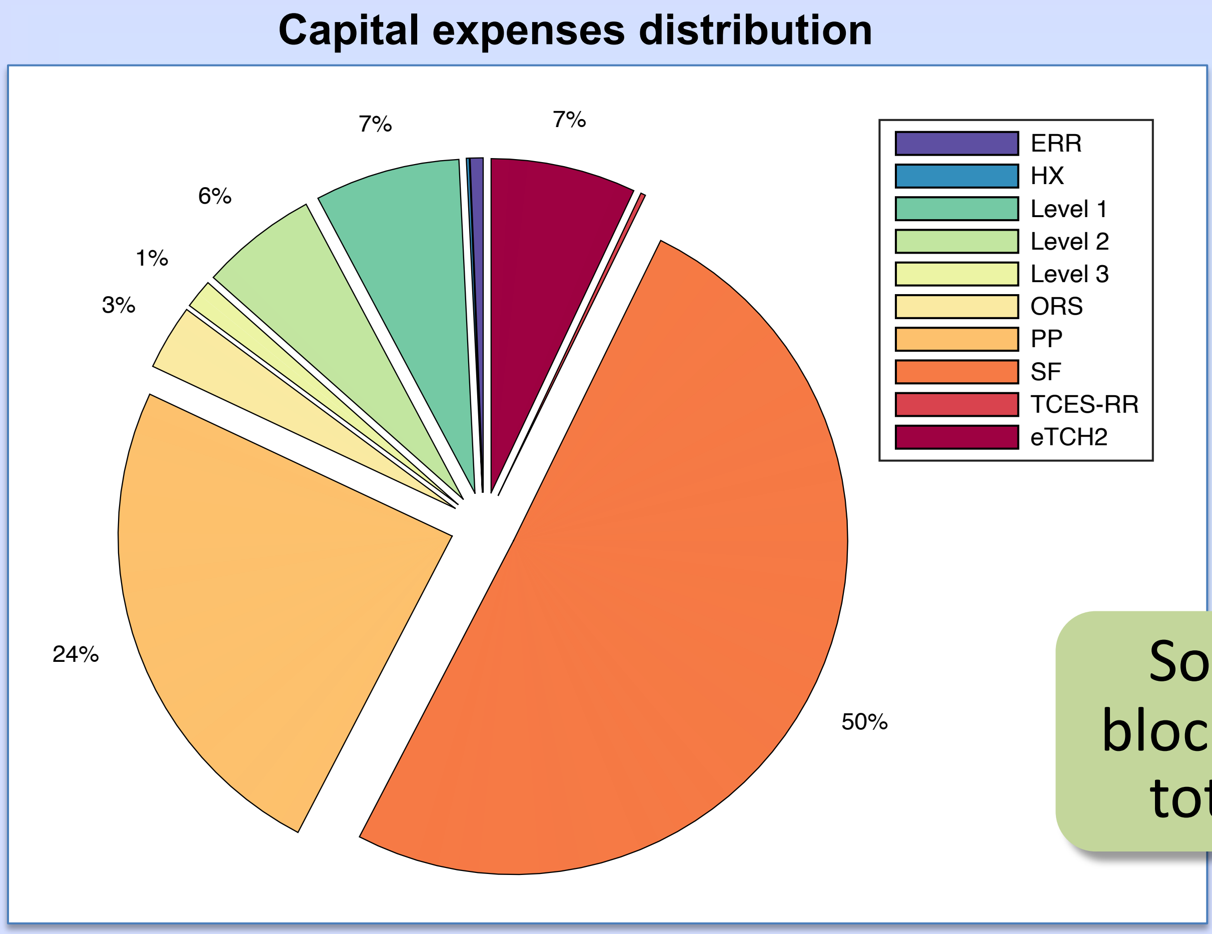


Results: multi-level energy storage L1-L2-L3 system



Solar plant and power block make up 74% of the total investment costs

Summary

- Three receiver configuration with 90-degree difference between each other exhibits the lowest LCOH
- L1-L2 LCOE is 15% above the baseline LCOE, but has a “guaranteed” dispatchable generation
- L1-L2-L3 LCOE is 16% less than baseline LCOE due to H_2 revenue
- To make this system profitable we need low off-peak electricity rates for filling storage or H_2 generation

Thank you for your attention!!

We would like to acknowledge the team and institutions involved in this work

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