

## **PROGRESS REPORT for EPC-19-060**

**November 2021**

Recipient Project Manager: Sarah Kurtz

Commission Agreement Manager: Jeffrey Sunquist

### **What we planned to accomplish this period**

1. We will submit the materials for the November public workshop
2. We will participate in the November public workshop and write a summary of the workshop
3. We will continue work on the multiple papers.
4. We will continue to meet with stakeholders and community representatives to gather inputs and request feedback
5. We will continue working with E3 to implement the first steps of a plan about the changes to RESOLVE

### **What we actually accomplished this period**

*1 and 2. November public workshop*

The materials for the November public workshop can be viewed at <https://www.energy.ca.gov/event/workshop/2021-11/staff-workshop-strategies-model-long-duration-storage> . We are not attaching them here to avoid big attachments in emails. The submitted files include a PowerPoint presentation and two draft reports.

The workshop stimulated interactions with multiple individuals. A summary of the email correspondence was prepared. A copy of that summary is attached for reference. Additional follow up to the workshop will be discussed during the next management call. Note: an email exchange in early December determined that the workshop summary due date should fall about 10 days after public comments were received. So, the initial summary of email exchanges is summarized here and the final workshop summary will be included in the December monthly report.

The CPR #2 is tentatively scheduled for Jan. 11. The content of CPR #2 should be discussed during the next management call.

*3. Continued work on multiple papers:*

Updates on the multiple paper status are summarized in Table 1:

Table 1. Papers that are in progress. New developments are in **bold**.

Topic of paper	Targeted journal	Status	Lead author	Primary conclusion/impact
1a. Defining long-duration storage	Issues in Science and Technology	Published	All	Defining long-duration storage broadly will stimulate innovation
1b. Defining long-duration storage	Joule	Published	Noah Kittner	Defining long-duration storage broadly will stimulate innovation; define taxonomy
2. Seasonal challenges	PVSC conference proceedings	Published	Mahmoud Abido	Seasonal storage in a solar-driven grid will show minimum energy storage during the winter
3. Seasonal challenges	iScience	<b>Accepted and in press</b>	Mahmoud Abido	Biggest challenges to resource adequacy will occur during the winter unless off-shore wind or a flat or dispatchable generator is added
4. Review of currently available storage technologies	Renewable and Sustainable Energy Reviews	Under review by journal	Rui Shan and Jeremiah Reagan	There are many storage options, some of which have the potential to replace existing fossil fuel plants
5a. Analysis of winter-dominant on-shore wind resource in California	Renewable and Sustainable Energy	<b>Review has requested revisions that will improve the paper</b>	Zabir Mahmud	A small number of wind generators in California generate more electricity in the winter than in the summer. We are assembling data to assess how consistently this is seen and to assess what fraction of California could show winter-dominant wind generators.
5b. Analysis of storage applications and effect of off-shore wind	Joule	Data are being recalculated based on paper 5a and other results. Data are being organized for first draft	Zabir Mahmud	The amount of diurnal storage needed is about a quarter of a TWh. If the grid is solar dominated, the diurnal storage is used > 350 times/y. If wind is added, we still need the same amount of diurnal storage, but it will be used much less frequently...
6. Time sampling in modeling of storage	<b>Joule</b>	<b>Manuscript is being prepared for submission</b>	Pedro Sanchez	What is the effect of choosing different time periods on modeling long-duration storage?
7. Impact of load shifting	PVSC conference proceedings	Published	Ashling Leilaoui	Impact on revenue when load shifting is used to move load from the head of the duck to the belly of the duck
<b>8. Value of south-facing tilt</b>	<b>PVSC or journal</b>	<b>Draft being developed and discussed</b>	<b>Russ Jones</b>	<b>Understanding the benefits of using south-facing tilt to reduce seasonal storage. It may be that a primary benefit is being able to better use the surplus electricity.</b>

*Paper #3: Seasonal changes:* The resubmitted version was accepted and is now working its way through the publication process. The final version will be attached to the next monthly report.

*Paper #5a: Winter-dominant wind:* The review by Renewable and Sustainable Energy suggested multiple useful revisions. We anticipate that the next submission will be accepted.

*Paper #5b: Statistical analysis of storage needed as a function of mix of generation:* The calculations have been repeated with the revised version of the code and the manuscript is being assembled.

*Paper #6: Time sampling for capacity expansion planning:* The manuscript is being prepared for submission to Joule.

*Paper #8: Optimizing the configuration of photovoltaic plants to minimize the need for storage:* An abstract is being prepared for submission to PVSC. A manuscript is also being prepared.

“*Development in Long-Duration Energy Storage Technologies*” was presented to the 38<sup>th</sup> USAEE/IAEE North American Virtual Conference on Nov. 2, 2021 by Rui Shan on behalf of Rui Shan, Jeremiah Reagan, Sergio Castellanos, Sarah Kurtz and Noah Kittner. The slides are attached to this report.

*4. Stakeholder and collaborator meetings:* During the month of November, we met with:

- Roderick Go at E3
- Julia Prochnik of Long Duration Energy Storage Association of California
- Roger Aines of Lawrence Livermore National Lab
- Sergio Duenas of Strategen – he made presentation for our Friday meeting
- Sarah Kurtz made presentation to UC Davis that included discussion of storage
- Public workshop stimulated interactions as noted in the attachment

*5. Continue work with E3 to develop a plan about the changes to RESOLVE*

We have downloaded solar and wind data from NREL and are in the midst of organizing the files. Recalling our plan:

For solar:

1. Identify the location (or set of locations)
2. Identify the year
3. Extract the irradiance data relevant to the location and year using satellite data available in the National Solar Radiation Database (NSRDB) and store in a file with both temperature and irradiance
4. Identify the orientation of installation
5. Calculate the hourly solar electrical generation profile based on the irradiance data, temperature data, and common solar panel properties for each selected orientation and system configuration (see below)
6. Define how to use the multiple locations into a representative “resource”
7. Calculate the generation file for each identified representative resource from the average of the generation profiles for that resource, weighted by the anticipated potential capacity for that specific location.
8. Verify confidence in the data by comparing to existing data sets

For wind:

1. Identify the location (or set of locations)
2. Identify the year
3. Identify the power curve
4. Identify the height of the turbine
5. Using the simulated wind-speed data from NREL's Wind Toolkit and the selections from steps 1-4, calculate the hourly wind generation profile for each location in the set of locations.
6. Define how to use the multiple locations into a representative "resource"
7. Calculate the generation file for each identified representative resource from the average of the generation profiles for that resource, weighted by the anticipated potential capacity for that specific location.
8. Verify confidence in the data by comparing to existing data sets.

In November we have been working on steps 4 through 8 for solar as well as some of the steps for Wind. We are also preparing to process these resource files to create the input files with variable time steps as well as full 8760-hour data from multiple years.

For step 4 for solar, we have selected four system designs:

1. One-axis-tracked horizontal-tilt with DC/AC=1.3. This duplicates the current design used by E3 in RESOLVE
2. South-facing latitude-fixed-tilt with DC/AC=1.3
3. One-axis-tracked, south-facing latitude-tilt with DC/AC=1.3
4. South-facing latitude-fixed-tilt with DC/AC=1.5.

The reason for using the higher DC/AC ratio for the fixed system is that there are fewer hours per year when that system will be putting out full power, so the clipping will be less serious than for the others.

### **How we are doing compared to our plan**

The creation of the full-year generation profiles for the multiple candidate solar and wind resources is taking longer than we expected. However, we are pleased that it looks like the first phase of the project will result in a total of 10 publications, the majority of which will be peer-reviewed publications. We have also presented at multiple events and expect to be participating in multiple additional events in the next year.

### **Significant problems or changes**

No change from last month.

### **What we expect to accomplish during the next period**

1. We will complete the public workshop report to respond to the public input

2. We will discuss plans for the January CPR with our manager
3. We will continue work on the multiple papers with a goal of having all of them submitted (maybe except one) by the end of the month
4. We will continue to meet with stakeholders and community representatives to gather inputs and request feedback
5. We will accelerate our work on implementing the baseline in RESOLVE. We will provide a summary of the resources for RESOLVE and how the data have been derived

**Status of Milestones and Products.**

<b>Task #</b>	<b>Task</b>	<b>Deliverable</b>	<b>Due date</b>	<b>Status</b>
1.2	Kick-off meeting	Updated budget	9/18/2020	Complete
1.3	CPR Meeting #1	CPR Report	TBD	
	CPR Meeting #1	CPR Meeting #1	TBD	
1.4	Final meeting	Final Meeting	11/11/22	
		Schedule for closeout	11/18/22	
		Draft and Final Written Products	11/18/22	
1.5	Progress Reports & Invoices	Progress Reports	Monthly	Ongoing
		Invoices	Monthly	Ongoing
1.6	Final Report	Draft Outline	6/30/22	
		Final Outline	TBD	
		Draft Report	8/30/22	
		Final Report	10/31/22	
		Written Responses to Comments on Draft Report	9/15/22	
1.7	Match funds	Status letter	9/9/20	Revision submitted
1.9	Subcontracts	Final subcontracts	TBD	Awaiting CEC approval of revised budget
1.10	TAC	List of potential members	9/9/20	Completed
		List of TAC members	TBD	Completed
		Documentation of TAC member commitment	TBD	Completed
1.11	TAC Meetings	Draft TAC meeting schedule	10/1/20	Completed
		TAC meeting 1	11/4/20	Completed
		TAC meeting 2	8/5/21	Completed

		TAC meeting 3	2/3/22	
		TAC meeting 4	11/2/22	
		Note, each meeting need multiple actions		
		Final TAC meeting schedule	TBD	Completed
		Draft TAC meeting agenda	TBD	First one completed
		Backup materials	TBD	First one completed
		Final TAC Meeting agenda	TBD	First one completed
		TAC meeting summaries	TBD	First one completed
2.1	Data assembly	Draft baseline description	2/4/21	Completed
		Final baseline description	2/25/21	Completed
2.2	Confirmation of baseline data and approach	Draft modeling approach description	2/4/21	Completed
		Final modeling approach description	2/25/21	Completed
2.3	Implementation of baseline data into models to create initial baseline scenario	Summary of baseline model results	3/23/21	Completed
		CPR Report #1	15 days prior	Completed
3.1	Evaluate and document future energy storage technology alternatives	Draft storage Technology summary	7/2/21	Completed
		Final storage technology summary	8/12/22	
3.2	Define representative future energy storage technology alternatives	Draft proposed storage scenarios summary	4/1/22	
		Final	8/12/22	
3.3	Evaluate and document future energy electricity generation technology alternatives	Draft electricity generation technology summary	8/2/21	Completed
		Final	8/12/22	
3.4	Define representative future electricity generation technology alternatives	Draft proposed electricity generation scenarios summary	4/1/22	
		Final	8/12/22	

4.1	Multi-day model optimization	Summary of multi-day baseline model results	9/2/21	Completed
		CPR #2	<b>Summer</b>	
4.2	Grid scenario selection	Draft grid scenario summary	10/11/21	Requires RESOLVE to be functioning
		Final	12/13/21	
5.1	Preliminary Scenario Analysis	Draft preliminary analysis summary	2/11/22	
		Final	4/15/22	
5.2	Final scenario analysis	Draft final analysis summary	6/10/22	
		Final	8/12/22	
6.1	Initial public meetings	Opening workshop presentation materials	11/17/20	Completed
		Northern CA workshop	12/3/20	Completed
		Southern CA workshop	12/3/20	Completed
		Opening workshop summary	1/8/21	Completed
6.2	Public workshop for grid scenario selection	Agenda	11/2/21	Completed
		Presentation materials	11/2/21	Completed
	Public workshop with CEC and TAC to present proposed scenarios		11/16/21	Completed
		Workshop summary	11/23/21 Summarize public comments: 12/17/21	First draft is attached
6.3	Public workshop for preliminary scenario analysis	Agenda	3/3/22	
		Presentation materials	3/3/22	
	Public Workshop with CEC and TAC to present preliminary analysis		3/18/22	
		Workshop summary	3/25/22	

6.4	Public Workshop for Final Scenario Analysis	Agenda	7/1/22	
		Presentation materials	7/1/22	
	Public workshop with CEC and TAC to present final analysis		7/15/22	
		Workshop summary	7/22/22	
7	Evaluation of Project Benefits	Kick-off meeting benefits questionnaire	9/18/20	Completed
		Final meeting benefits questionnaire	10/14/22	
8	Knowledge transfer activities	Draft initial fact sheet	7/23/20	Completed
		Final initial fact sheet	7/30/20	Completed
		Draft final project fact sheet	7/21/22	
		Final project fact sheet	7/28/22	
		Draft knowledge transfer plan	12/31/20	Completed
		Final knowledge transfer plan	2/26/21	Completed
		Draft knowledge transfer report	8/30/22	
		Final knowledge transfer report	10/31/22	

**PROGRESS REPORT for EPC-19-060**

**Second Public Workshop Summary**

**Workshop date November 17, 2021**

Recipient Project Manager: Sarah Kurtz

Commission Agreement Manager: Jeffrey Sunquist

**Staff Workshop for the Second Public Workshop for Comments on Long Duration Energy Storage Scenarios**

The workshop was held via Zoom on Wednesday, Nov. 17 2021 at 1 pm, as advertised at <https://www.energy.ca.gov/event/workshop/2021-11/staff-workshop-strategies-model-long-duration-storage>. The presentation and two draft reports are posted for public comment.

**Agenda:**

1:00 Welcome (Sunquist, Kurtz)

1:05 Understanding California's long-duration storage options (Kittner)

1:20 Questions

1:30 Talking about long-duration storage (Kurtz)

1:35 Understanding how California's generation mix affects storage needs

Draft report – seeking public comment before finalizing next modeling

1:50 Approach to modeling value of long-duration storage

Draft report – seeking public comment before finalizing next modeling

2:05 Questions

2:20 WECC-wide modeling (Hidalgo-Gonzalez)

2:30 Questions

3:00 Adjourn

## Summary of communications

Unfortunately, no recording is available, so this summary documents email correspondence after the workshop rather than a summary of the discussion during the workshop.

The following table provides a summary of correspondence

External contact	Inquiry	Follow up
Mike Gravely	Information relevant to solicitations	Email correspondence – see below. Additional discussions possible
Shucheng Liu	Battery safety and weather issues	Have not studied, but could consider for future work
Peggy Beltrone	Request for recording and Patricia's email	No recording, but sent Patricia's email
Alan Lamont	Multiple comments	Continued discussion
Bret Adams	Feedback on presentation	Continued discussion
Sean Soni, Priscilla Hamilton, Kevin Barker (So Cal Gas)	Asked question about hydrogen storage	They will give formal written input and follow up with a meeting
Sophie Meyer (Form Energy)	Include input from Form Energy	Will provide input to report

### From Mike Gravely:

*Jeff, Sarah,*

*I am trying to determine if any of the research or capability you have can help me as I make planning decisions for how to spend \$300M to \$400M on Long Duration Energy storage starting in 2022. After today's discussion, it seems you are doing great modelling but do not have a lot of information to help in the short term decisions the CEC will be making in 2022.*

*Let me know if I have it wrong.*

*Mike*

### Response:

*Hi, Mike,*

*I apologize for being slow in responding, but here are a few thoughts. These are organized according to the logic, not according to how to write a solicitation. I'm assuming you can put them into that form, though I could try to do that if that would be helpful.*

*And/or, would it be useful if I expanded this to include some quantitative graphs? In terms of being helpful to you - what I learned at NREL is to always write the solicitation very broadly, then fund the strongest teams to do projects that looked promising. I've spent some time composing this message, but I have a concern that I've totally missed the mark in terms of what you're looking for, so it might be better to chat...*

If you can predict the future, you will be in a much better position to make wise decisions. Pivotal questions include (A and B):

**A.** Do you think the state will use mostly solar for generation or will offshore wind, a large transmission line from Wyoming, and/or new technology that increases onshore wind potential enable a substantial increase in wind relative to solar?

**B.** Do you think that we will begin a massive use of renewable electricity to make hydrogen that will then be used for many things? This could happen to the tune of doubling the installed electricity generating capacity. There are many questions related to hydrogen storage and transport. LBL estimates that 6% of the current load can be shifted before Li storage becomes more economical today (that's a simplification, of course). If 50% of our electricity is fed to electrolyzers, this would be almost a factor of 10 increase in our ability to use demand management changing how we think about storage vs flexible loads.

**Addressing diurnal applications (which will need to be addressed first - today we see about 4 GWh being used every day - this will continue to grow, enabling more solar to be installed)**

If solar dominates, then for diurnal applications you will need storage that is

1. Low cost
2. High efficiency - 90% would be a "nice" target
3. Long life (>10,000 cycles with little degradation would be good)
4. Scaleable to at least 0.3 TWh\* with ability to deliver >40 GW, by sometime in the 2030s. Note that this could be delivered by 10 GW of 4 h storage plus 30 GW of 9 h storage or a range of other combinations. The build out should occur in parallel and in balance with the build of more solar.

If wind grows more, then the requirements are modified somewhat:

1. Still need low cost, of course
2. Efficiency is still useful, but storage will not be used as much, so a lower efficiency will have less impact. 90% would still be great, but 80% would also be a good outcome. (note that today's batteries deliver 80% on average, with the best ones delivering 90%, so it's hard to think of targets that are lower unless a lower cost can justify it)
3. Only a small fraction of the diurnal storage will be used every day, so cycle life of >3000 should be adequate.
4. For diurnal, still need at least 0.3 TWh\* with ability to deliver > 40 GW, but see below.

\*The 0.3 TWh is based on good transmission without much need of storage to address congestion problems.

**Addressing seasonal applications (which is already affecting pricing, though not yet resource adequacy)**

If **hydrogen** generation provides a large flexible load, then the seasonal imbalance will largely be met by turning off the electrolyzers during the winter. Additionally, the hydrogen may be used to provide electricity during the most challenging times. Investments in hydrogen may or may not be called "long duration storage" especially when that hydrogen may never be used for electricity generation, but these investments may be some of the most important. Also note: if the generation is doubled to meet the electrolyzer load, the diurnal storage requirement will also double relative to what I've described above.

The seasonal imbalance can be partially met by the selection of the type of **solar** and **wind**. We need more analysis to be confident of the timing, but there is evidence that typical daytime prices in winter are already higher than in summer, so it would be good to start thinking about this - the electrolyzers won't become significant until much later, so it may be useful to start thinking about this soon.

**Addressing cross-day applications (Note that as long as you've retained some natural gas plants to meet peak load during the summer, the cross-day applications may not become critical, so I anticipate the requirement for these may emerge later, but higher natural gas prices may hasten the day when they become cost effective)**

For cross-day applications you will need storage that is

1. Still low cost (of course)
2. Cycle efficiency is not as important but low idle losses become very important as the charge must be maintained for weeks while waiting for the time when it is needed.
3. Cycle life of 1000 or even 300 may be adequate

We anticipate that as storage is used more and more, you will see that a 12 h battery may be used on a daily basis to provide 4 h of electricity, resulting in a depth of discharge of 33%, enabling very little degradation to the battery and

*used only once a month (on average) for the full 12 h discharge - causing more degradation for that deep discharge, but if it's only once per month, then it's not a big deal. So, these things aren't black and white. This approach may enable Li batteries to make it further than seems feasible now when they are limited by their lifetime.*

*The metrics of cost (and scalability), efficiency and life are most important, but other metrics to ask to have addressed:*

- Use of local labor*
- Permitting time (environmental concerns)*
- Land usage, etc.*

*I suspect that there are no surprises here, but I hope that you find at least something useful in what I've written!*

*Sarah*

## **From Shucheng Liu**

*Hi Sarah,*

*Congratulations on a successful workshop on Tuesday. The presentations were very impressive.*

*I am reaching out to you to get your input about forced and planned outages in battery storage modeling. In our PLEXOS models for resource planning, the outage of battery storage is not considered. However, based on observations from the ISO operation, it is a factor that should not be overlooked. The challenge is that we do not have solid data for estimating the outage rates.*

*Do you know if the studies in your project consider outages of battery storage, or if the survey of the energy storage industry collected any information about it?*

*Thank you,*

*--Shucheng*

## **Response:**

*Hi, Shucheng,*

*We have not studied this and I have not seen good data.*

*May we surmise that battery storage is going off line because of*

- safety issues (I heard of a fire/smoke that made a lengthy shut down - I hope that this sort of thing will be solved through technology development and standards that will prevent overheating incidents)*
- weather variability related to overheating or being too cold - this could be addressed by HVAC installations, but that adds both cost and requires energy inputs, so may not be universally applied, resulting in an ongoing issue.*

*Are these the sorts of things you are seeing?*

*We are always happy to go a new direction if we can make a difference with a new study... The multi-month shut downs could be easily studied using EIA 923 data. I already have a student looking at the EIA 923 data, so I could ask him to see if there is evidence of common problems.*

Sarah

**From Alan Lamont:**

*Hi Prof Kurtz*

*I listened in to your team's presentation of the CEC study on long duration storage. Storage, along with with the cross sectoral use of energy products, is one of my main interests. I have a few thoughts that might be helpful to the team as they study these issues and as they interpret the results of the modeling.*

*My notes fall into two areas. First, the analysis found that a system with high solar and low wind was optimal. This result appears in other models and in some of my work. I find that it is driven by assumptions about storage technologies. It may be useful to discuss that, although the team may already be fully aware of the behavior. Second, the analysis on slides 37 and 38 show the cycling of different bins of storage capacity. It was mentioned that it would be useful to have a discussion of the types of storage that could serve the time patterns of storage for each bin. This can be approached from the underlying economic theory of storage. The discussion below walks through the theory and discusses how it might be used to evaluate the economic viability of different types of storage in different roles in Slide 38.*

***Relationship between assumptions about storage technology and optimal system configurations.***

*In the current analysis wind has relatively small value in this system compared to solar, and only a small wind capacity is deployed. It is also shown that storage goes to minimum during the winter and reaches maximum during the summer. This is may be a result of the assumptions about storage technologies.*

*It appears that the current analysis assumes batteries as a storage medium. These are expensive per kWh of storage. When batteries are the storage medium, the models tend to deploy just enough energy storage (kWhs) to get through a couple of days. To make the system work, this small amount of storage needs to be charged every day or so. The only way to reliably do this is through solar, since it tends to be available pretty much every day. The optimal solutions under these conditions are systems with large solar, small wind, and enough storage to get through a few days of low generation.*

*Because the optimization deploys small energy storage capacity the wind capacity has a relatively small value. The wind blows intermittently. It might be strong for several days, or weeks, and then be quiet for days or weeks. When it is blowing, quite a bit of energy is produced. But if the system cannot use it directly it must either be stored or lost. When small*

*storage capacity is available, it is often full or fills up quickly, so it cannot accept any more energy. The wind energy is lost, so wind capacity has relatively little value, and the optimization model deploys little wind capacity.*

*This suggests that the model may give a different result if a storage technology is introduced that operates economically on a seasonal basis. When storage is operating on a seasonal basis, a large energy capacity is needed. This shows up in slide 38. For the optimization to deploy a large energy capacity, the technology has to be cheap per kWh. Such a technology can be hydrogen, if geologic storage is available, pumped storage, if the topography allows it, or ammonia. I noted that ammonia was mentioned in the study. It has the advantage that large quantities of liquid ammonia can be stored in relatively cheap tanks. Of course, we have to make the ammonia and liquify it, so it is not very cheap to produce it, just cheap to store it.*

*If the analysis can be expanded to consider these other storage technologies, it would give a useful comparison of different approaches. But, to model seasonal storage, we pretty much need to model a full year, 8760 hours. It was stated that the team is planning to do this using the RESOLVE model. Given that the use of 8760 hours requires a very large number of equations in an LP framework, nearly all analyses that I am aware of use samples of days. SWITCH and RESOLVE are both structured to model samples of days. I would be very interested in understanding how the new version of RESOLVE has been structured to handle 8760 hours.*

### **Discussion of a way to use the analysis on slides 37 and 38**

*The question was raised about which technologies would be deployed for the different roles shown in slides 37 and 38. The theoretical economics of storage can help provide a concrete explanation for the choice of storage technologies in each part of the diagram. The discussion here is based on the paper on storage that I sent a little while ago.*

*Using the theory, we should be able to review the results of the optimization run to identify sequences of system prices (the shadow price on the constraint that the load must be met each hour) that determine the economic viability of different storage technologies, or the prices that would make a technology viable.*

*I hope I am not explaining things that the team already knows*

### **Here's the economic theory of storage**

*The optimization models find the system configuration such that the marginal value of each technology is just equal to its marginal cost. When some technology has been deployed to a given level, we can ask the whether or not adding another increment of capacity (a "marginal" increment) would be worthwhile. We increase the capacity of a technology up to the point that the value of a marginal increment is equal to the cost of the marginal increment.*

*The "marginal value" of the technology is the value provided by adding another increment of capacity to the system. Generally by adding an increment of power to a generator, or adding an*

*increment of stored energy to storage, that increment can be used to back down an expensive generator during peaks. It might also allow us to reduce the capacity of another generator. This reduces the total cost of the system. But, adding that increment of capacity costs something. In the case of a generator, it costs the operating cost and the capital cost. In the case of adding an increment of energy storage, the cost is the cost of generating the energy needed to charge the additional increment of capacity.*

*We note that as we increase the capacity of the technology, its marginal value tends to decrease. So a small amount of a technology might be worth its cost, but the amount that can be added is limited. Generally speaking, its marginal cost is pretty constant. Let's just talk about the value of adding energy capacity (kWh) to the storage. Charging and discharging capacity are also important, but that is a different discussion and is not very relevant to slides 37 and 38.*

*In the case of storage, adding another kWh of energy capacity provides some value by providing an increment of energy that can be used to back down some other, expensive generator when it discharges. At the same time, to make that increment of energy available, the storage has to be charged by taking energy from the grid. This is a cost. The marginal value of an incremental unit of storage is a function of the difference between the value of the energy when it is discharged and the cost of acquiring the energy when it is charged. This difference is counted when the storage completely cycles--completely charges and discharges. That is when the additional cost and the additional value are realized.*

*When we talk of the value of discharging and the cost of charging, we need to take into account the efficiency and operating cost of charging and discharging. For example, if the charging process is only 50% efficient (in the range of hydrogen) the storage will have to purchase 2 kWh of electricity in order to put 1 kWh into storage. So the cost will be 2x the system price in that hour. If there are other operating costs associated with putting the kWh into storage, these must be counted also. Similarly to charging, if the discharge process is only 50% efficient, discharging 1 kWh of stored energy will result in just 0.5 kWhs actually put onto the grid. So the value of the discharging is 0.5 times the marginal price at that time.*

*The fact that many storage technologies self-discharge may also be important. This is somewhat analogous to the efficiency losses. The analysis should take into account the length of time between the marginal charging and the marginal discharging to determine how much energy is lost and how much can be discharged to the system.*

*Like everything else with energy, the full story is a little more complicated. If we add an increments of storage, it will charge at the highest price that storage charges at. Previous increments of storage will already have charged at lower prices. The additional increment of storage will also discharge at the lowest price that storage has discharged. As we add storage capacity, each increment will charge at a somewhat higher price and will discharge at a somewhat lower price. So as a result of adding capacity, the marginal value of storage capacity*

*will naturally decrease. In the optimal solution, it will decrease to the point where the marginal value is just equal to the marginal cost.*

*Every time that the storage is completely cycles, the storage earns this difference between the value of discharging and the cost of charging. Therefore, the total annual marginal value of the increment of storage is the value earned each cycle times the number of cycles over the year.*

### ***Relationship of the theory to the chart on slide 38 showing frequency of cycling for different bins of storage***

*The chart identifies capacities of storage, or bins, that are cycled frequently--some of it every day. Even if the difference between the value of discharging and the cost of charging is small on each cycle, the sum over the year can be large. This means that a storage technology that is fairly expensive, such as batteries, can be economic in this role. But we note that the chart points out that this is a small capacity that is cycled each time. So a fairly expensive technology can be economic, but only a small amount of capacity.*

*The chart goes on to identify capacities (or bins) that are cycled less often. Lets consider the bins that are cycled once per year--seasonal storage. Each year this will only earn one cycle's worth of the differential between value of charging and cost of charging. To be economically viable, there either must be a very large differential between the value of discharging and the cost of charging, or the technology must be very cheap, or both.*

*Based on the results of the optimization models, it should be possible to extract the prices of electricity in the hours that the system charges and discharges. Based on these prices, and the number of cycles, we can directly compute the value of a storage technology in that role.*

*As mentioned above, the calculation does have to account for the charging and discharging efficiencies and any operating cost. Consequently the analysis for each bin of storage should be done with a particular storage technology in mind.*

*Using this analysis framework, different storage technologies can be evaluates. The analysis should be able to determine at what price the technology would become viable. If efficiency is a issue, the analysis can show impact of further research to improve the efficiency.*

*If you find these sorts of comments useful, i would be glad to expand on them in the future.*

*Best  
—Alan Lamont*

### **Response:**

*Hi, Alan,*

You've given a comprehensive response to the workshop - thank you for your input.

I'll respond to a few items below.

On Nov 20, 2021, at 11:05 AM, Alan Lamont <[alandlamont@earthlink.net](mailto:alandlamont@earthlink.net)> wrote:

Hi Prof Kurtz

I listened in to your team's presentation of the CEC study on long duration storage. Storage, along with with the cross sectoral use of energy products, is one of my main interests. I have a few thoughts that might be helpful to the team as they study these issues and as they interpret the results of the modeling.

My notes fall into two areas. First, the analysis found that a system with high solar and low wind was optimal.

While it is true that the RESOLVE reference portfolio selects very little wind, it selects all wind that it is offered. The wind it is considering blows more at night, so if it could use more it would be able to balance solar during the day with wind at night.

This raises the question of how much wind would be feasible to deploy in California. As the wind technology evolves, the amount should increase - do you know of any good studies on how much wind it would be feasible to deploy in California?

This result appears in other models and in some of my work. I find that it is driven by assumptions about storage technologies. It may be useful to discuss that, although the team may already be fully aware of the behavior. Second, the analysis on slides 37 and 38 show the cycling of different bins of storage capacity. It was mentioned that it would be useful to have a discussion of the types of storage that could serve the time patterns of storage for each bin. This can be approached from the underlying economic theory of storage. The discussion below walks through the theory and discusses how it might be used to evaluate the economic viability of different types of storage in different roles in Slide 38.

### **Relationship between assumptions about storage technology and optimal system configurations.**

In the current analysis wind has relatively small value in this system compared to solar, and only a small wind capacity is deployed. It is also shown that storage goes to minimum during the winter and reaches maximum during the summer. This may be a result of the assumptions about storage technologies.

It appears that the current analysis assumes batteries as a storage medium.

No, the study I presented used a hypothetical storage reservoir without specifying its identity. The study was meant to understand the choice of generation technologies on the minimum storage requirement, so we did not attempt to identify the type of storage and no cost analysis was attempted. We will do that in the next phase of our work.

These are expensive per kWh of storage. When batteries are the storage medium, the models tend to deploy just enough energy storage (kWhs) to get through a couple of days. To make the system work, this small amount of storage needs to be charged every day or so. The only way to reliably do this is through solar, since it tends to be available pretty much every day. The optimal solutions under these conditions are systems with large solar, small wind, and enough storage to get through a few days of low generation.

Because the optimization deploys small energy storage capacity the wind capacity has a relatively small value. The wind blows intermittently. It might be strong for several days, or weeks, and then be quiet for days or weeks. When it is blowing, quite a bit of energy is produced. But if the system cannot use it directly it

*must either be stored or lost. When small storage capacity is available, it is often full or fills up quickly, so it cannot accept any more energy. The wind energy is lost, so wind capacity has relatively little value, and the optimization model deploys little wind capacity.*

*This suggests that the model may give a different result if a storage technology is introduced that operates economically on a seasonal basis. When storage is operating on a seasonal basis, a large energy capacity is needed. This shows up in slide 38. For the optimization to deploy a large energy capacity, the technology has to be cheap per kWh. Such a technology can be hydrogen, if geologic storage is available, pumped storage, if the topography allows it, or ammonia. I noted that ammonia was mentioned in the study. It has the advantage that large quantities of liquid ammonia can be stored in relatively cheap tanks. Of course, we have to make the ammonia and liquify it, so it is not very cheap to produce it, just cheap to store it.*

*If the analysis can be expanded to consider these other storage technologies, it would give a useful comparison of different approaches. But, to model seasonal storage, we pretty much need to model a full year, 8760 hours. It was stated that the team is planning to do this using the RESOLVE model. Given that the use of 8760 hours requires a very large number of equations in an LP framework, nearly all analyses that I am aware of use samples of days. SWITCH and RESOLVE are both structured to model samples of days. I would be very interested in understanding how the new version of RESOLVE has been structured to handle 8760 hours.*

*I went through this very quickly in the talk: I plan to reprogram RESOLVE so that it does the capacity expansion optimization using two time points per day (actually two to four, but let me explain the concept with 2). We will use the hour after sunrise and the hour before sunset to identify the amount of storage capacity we need to deploy. This enables us to look at 365 days per year in a computationally efficient way. Then we will look at the hourly dispatch using a second optimization that uses the capacity expansion plan from the first calculation. Please note that we have not yet done this, but I think it should work well. We have a lot of work to do to get the model running.*

## **Alan's response**

*Hi Sarah*

*Thanks for filling me in.*

*If there is something written on the model and analysis, I'd be glad to take a look at it.*

*Here are a couple of thoughts about running the model over a full year. Using RESOLVE with two time points per day may not get at a good optimum. Unfortunately, when it comes to optimizing over a full year (8760 hrs), it is very easy to see what is wrong with an approach, and really hard to come up with a better solution. I have been thinking about this quite a bit for the last couple of years. As soon as I come up with a better idea, I'll be sure to let you know.*

*But, your plan to then execute an hourly dispatch model with the capacities from the capacity expansion model is basically what I would have suggested. With this approach you can pull out the hourly system prices, and then you can compute the marginal values of each of the generators. If the marginal value is lower than the marginal cost, you can reduce the capacity. If the marginal value is higher than marginal cost, you can increase the capacity. Through a series of iterations, you can get closer to the optimal configuration. It may also be practical to run an optimization solver on top of the hourly dispatch model to do this automatically. This would basically be solving the problem through a market equilibrium algorithm rather than LP*

*We have done things like this using Plexos. I'm guessing you will use E3's software. I would not be surprised if E3 already has thought about something like this. They have a few people who understand this stuff at a very basic level.*

*Here's wishing you a good Thanksgiving*  
—Alan

**Response:**

*Hi, Alan,*

*It looks like I never responded to this. I took a nice holiday over Thanksgiving and am now trying to catch up on things.*

*We have our work cut out to get this going. Once we've got it running, I should touch base with you again! Thanks for all of your input!*

*Sarah*

**From Bret Adams:**

*Hi Sarah!*

*You may remember that we met over setting up with Mowafak's support, a Calisolar array in your outdoor test facilities at NREL and then periodically at various events.*

*I was pleasantly surprised to join the CEC modelling call last week to find that you are now engaged in energy storage. I went to high school up the road in Modesto area back when fog and daily overcast throughout the winter made living off 99 cold and dreary. I moved there from the eastern slope of the Sierras where we had temperatures down to -40 but found it colder living in the valley. I think this has changed with less Tule Fog, no hundred car crash ups for years ... welcome to California.*

*I found your approach and nuanced observations quite informative. I'm sure you run across a lot how people don't understand that renewables are both a driver for storage and a substitute; that the common wisdom that wind is the perfect complement to solar (on the assumption that solar is in the day and during the summer; wind is at night during the winter) may be true some places, but not universal; that there are different 'flavors' of solar and wind siting and design that have different impacts on the grid.*

*I in particular appreciated your call for a new taxonomy on storage. 10 years ago it was everything I could do to get people to also rate in \$/kWh and to differentiate power applications from energy applications. We formed the "LDES" stakeholder group under the CPUC arguing for considering the benefits of at least 4 hours of storage. Now some*

*(Imre Gyuk recently) are calling 10 hours 'MDES' and seasonal storage LDES. I guess 'short', 'medium' and 'long' will always be relative to the current average duration, so confusing. Even duration is confusing as in many technologies, the rated energy divided by rated power will not get you the same duration as you get running full power until no more energy left. As I think you were pointing out, duration meaning the same thing as charging time and discharging time isn't a really great definition either since in many applications, particularly solar, ideally you'd have different charging times than discharging times. Aggregating the performance characteristics and not the technology seems to also be a valid approach. ... and I could go on. Naming and taxonomy is important. It would be good to agree on some permanent names.*

*I'm glad to have learned about your work, will continue to follow, and hope our paths will cross again. If there's any support, data, or perspectives, or other that I can provide in support of your work, I'd be glad to do so. Modelling has always been a very important part of energy storage since in fact, it is much more complicated than solar or other generation's 'CoO' which is hard enough.*

*Much success,*

*Bret Adams  
+1 351.201.9139*

**Response:**

*Hi, Bret,*

*It's really nice to hear from you, and, especially to get your feedback on our presentation. It would be great to connect to hear more of your wisdom. Will you be at the Long Beach event in January?*

*Sarah*

**To Southern Cal Gas**

*Hi, Sean,*

*I was intrigued by your comment about underground storage of hydrogen at the Public Workshop on Nov. 17.*

*I had made a mental note to check the recording, but then there were technical difficulties and the technical recording was not available.*

*Would you mind repeating your comment either via email or by setting up a meeting to discuss?*

*I'm very intrigued by the possibility of doing great things with hydrogen and it's very possible that what I wrote about the potential for large scale storage of hydrogen did not properly capture the opportunity for small-scale hydrogen (I had meant to make a positive statement not a negative statement). I'd like to make sure to get it right, so would like to learn more from you.*

*Thanks!*

## **Response from Sean Soni (Southern California Gas):**

*Dear Dr. Kurtz,*

*We greatly appreciate your follow-up to the workshop and your research team's insights on the topic thus far.*

*Regarding our comment on hydrogen storage, it was about considering research that is currently in progress to determine if it is feasible to store hydrogen underground in other geologic formations, such as depleted oil and gas reservoirs and hard rock caverns. We plan to expand upon other constructive feedback points with our Written Comments that we will submit next week.*

*We are very enthusiastic about the opportunity to engage with your research team and will work with you to set up a meeting to discuss further. We also plan to include some of our subject-matter experts in the discussion.*

*Thank you again for your email, Dr. Kurtz, and looking forward to the next steps.*

*Kind regards,*

*Sean Soni  
Energy Policy Advisor  
Southern California Gas*

## **From Sophie Meyer (Form Energy)**

*Hi Jeffery and Sarah,*

*I'm a policy advisor for Form Energy, a company developing a low-cost, 100-hour duration iron-air battery for grid-scale applications. I believe you've worked with other members of my team on our EPIC-funded demo project, Jeffery. I'm reaching out about the CEC's recent Staff Workshop on Strategies to Model Long Duration Storage. I was unfortunately unable to attend the workshop and am only now catching up on reviewing the draft report.*

*Form would love to provide our technical specs and cost projections for inclusion in the report. In that interest, it would be great to connect to better understand the report process. For example, what specific information and formatting would be most helpful? Should we plan to submit our numbers via comments on December 7 or is there an opportunity to work with you more collaboratively? If we have other feedback on the report aside from sharing details about our own technology, what is best to share that feedback? Finally, what is the timeline for publication of the final report?*

*Please let me know if you're willing to set up a time to chat or just give me a call at 480.389.8228.*

*Best,  
Sophie*

## **Response from Jeff Sunquist:**

*Hi Sophie,*

*Thank you for reaching out and for giving your time to review the draft report. The final drafts of the storage technology report and the generation technology reports are due in August 2022, and the final project report is expected in October 2022. Work will begin on the preliminary scenario analysis this month and will continue through Q1 2022. The e-Comment system (<https://efiling.energy.ca.gov/EComment/ECommentSelectProceeding.aspx>) is the preferred method for submitting public comments. This workshop was filed under the 20-MISC-01 proceeding. However, I will defer to Sarah on what may work best for having a dialogue.*

*Thanks,  
Jeff*

*Jeffrey Sunquist*

**Response:**

*Hi, Jeff and Sophie,*

*It has been on our list to talk with Form Energy, so we are very pleased with the opportunity.*

*It will be great to have your input via the public comment process, but I would also be delighted to set up a time to talk with you.*

*Would 9 am (PST) on Friday, Dec. 10 work for you? I'm copying Noah Kittner, as I think he might be interested in joining the discussion.*

*Thank you for your interest,*

*Sarah Kurtz, PhD*

# Development in Long-Duration Energy Storage Technologies

Rui Shan<sup>1</sup>, Jeremiah Reagan<sup>2</sup>, Sergio Castellanos<sup>3</sup>, Sarah Kurtz<sup>2</sup>, Noah  
Kittner<sup>1\*</sup>

<sup>1</sup>, University of North Carolina at Chapel Hill, NC, USA

<sup>2</sup>, University of California, Merced, CA, USA

<sup>3</sup>, University of Texas Austin, TX, USA



38th USAEE/IAEE North American Virtual Conference

November 1 & 2, 2021

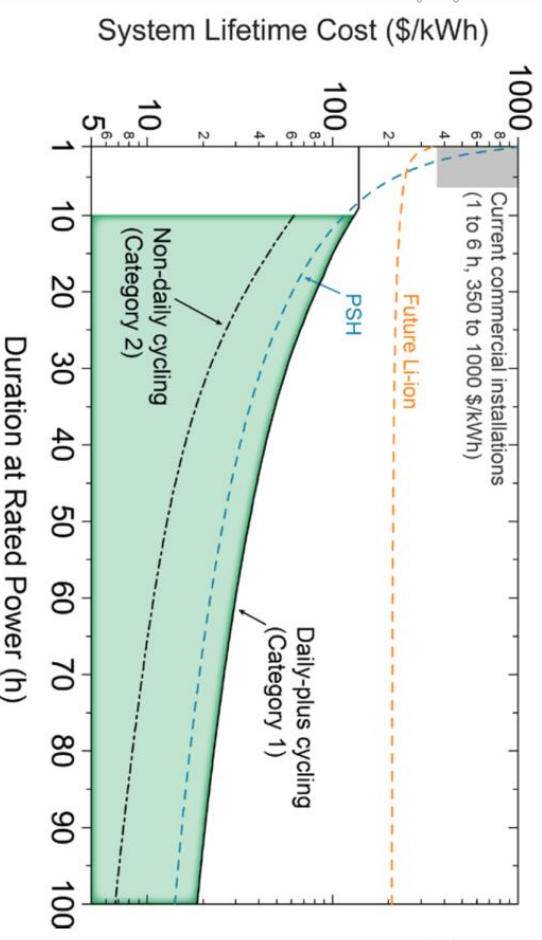


RESEARCH

# Background

## What is long duration energy storage?

- Long duration of discharging or storage?
- No widely agreed definition, but usually the technologies are
  - Large in energy and power rating
  - Decouple energy and power cost
  - Energy power ratio larger than 4
  - Average total capital cost decline fast as energy rating increase
- We suppose it could provide services like inter-day energy arbitrage and even seasonal energy storage

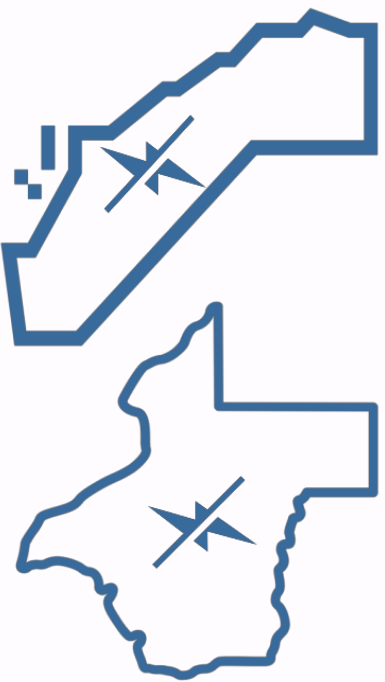


Source: Arpa-E, Duration Addition to electricity Storage (DAYS) Program Overview

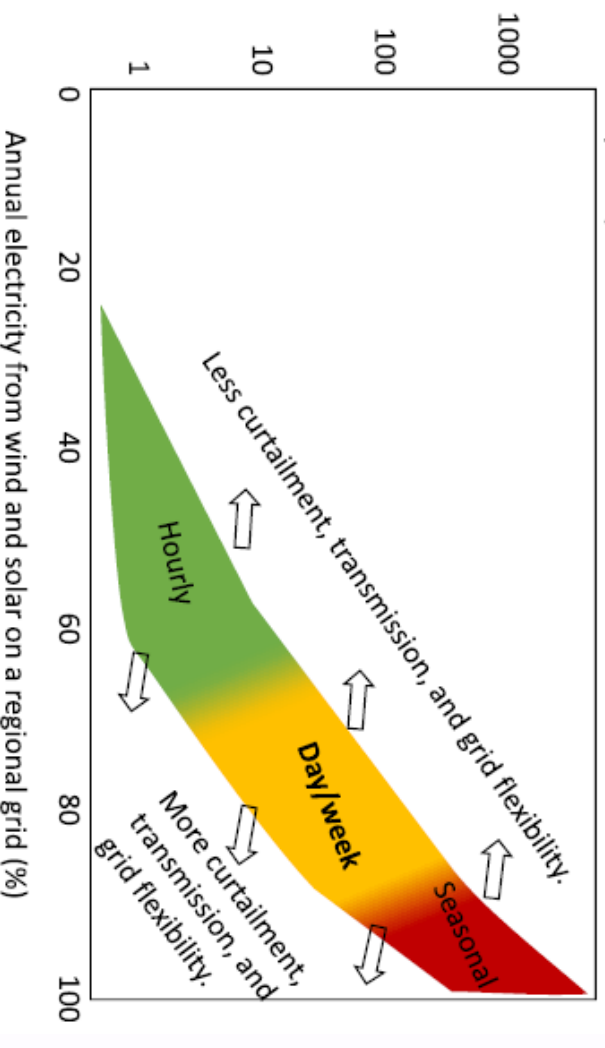
# Background

## Why we need long duration energy storage?

- Seasonal variation of solar and wind
- Regional resilience



Maximum required storage duration  
(hours at rated power)



Albertus, P., Manser, J. S., & Litzelman, S. (2020). Long-duration electricity storage applications, economics, and technologies. *Joule*, 4(1), 21-32.

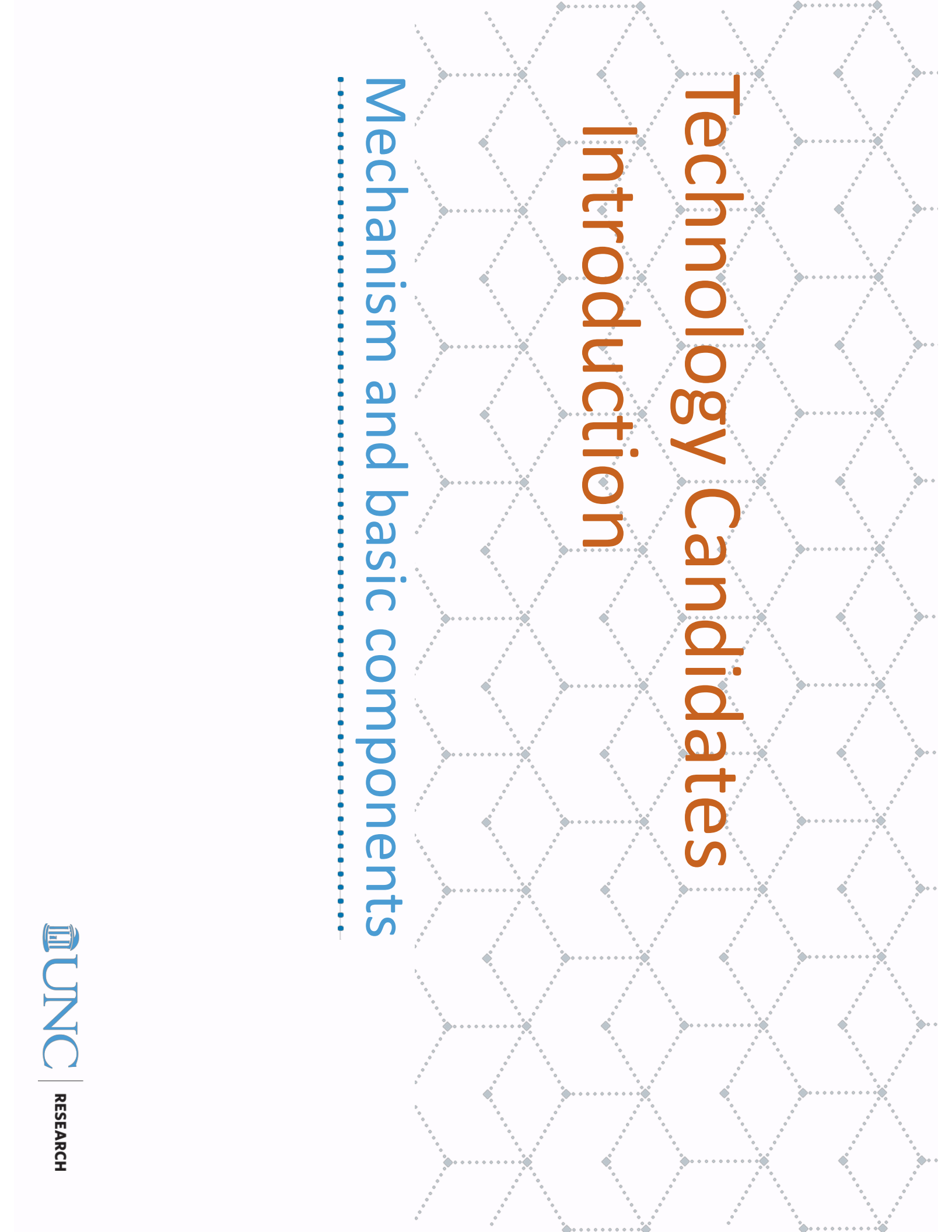
# Research Gap: metrics and new techs

## Metrics:

1. Land footprint
  - Large energy and power make land usage a concern
2. Equivalent efficiency
  - Storing for a long period makes the idle-loss a key consideration
3. Average capital cost not LCOS
  - LCOS involve many assumptions that may not be appropriate for LDES applications

## Technology candidates:

1. Pumped storage hydropower
2. Gravity other than water
3. Compressed air
4. Thermal
5. Flow battery
6. Hydrogen



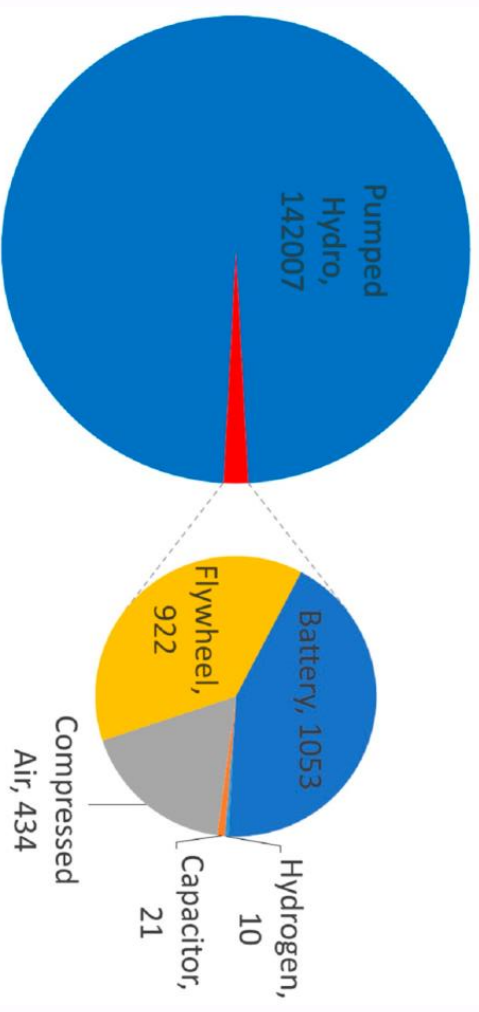
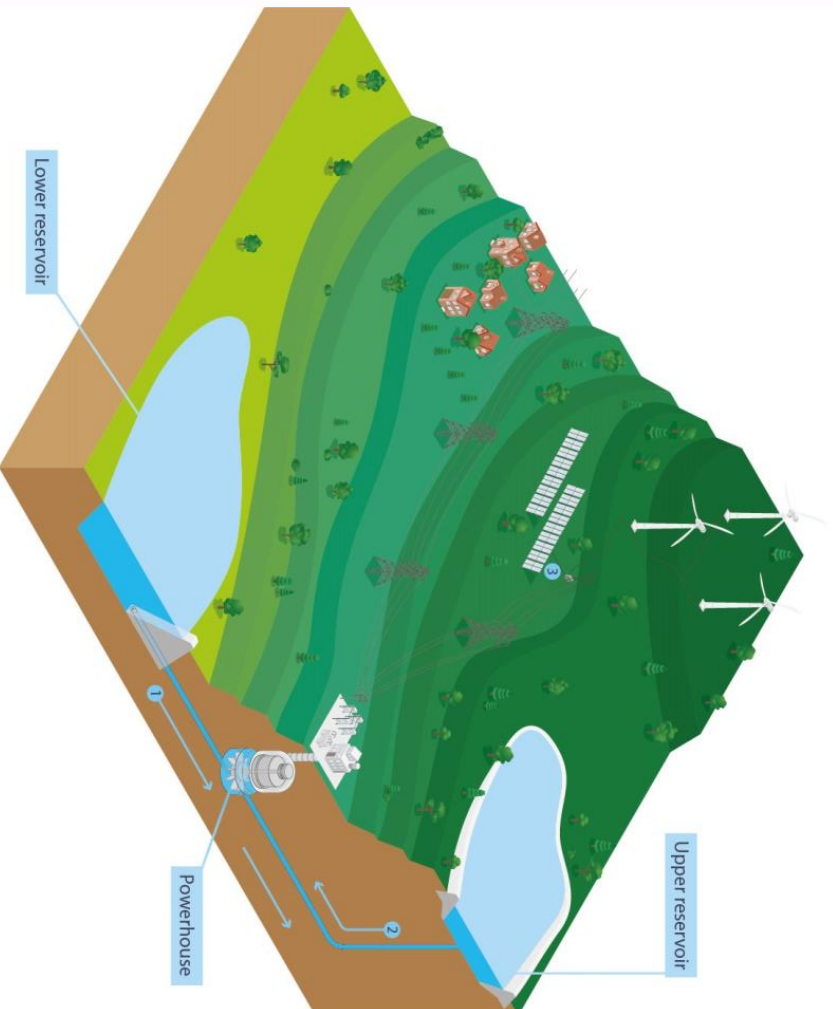
# Technology Candidates Introduction

Mechanism and basic components

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# Pumped storage hydropower

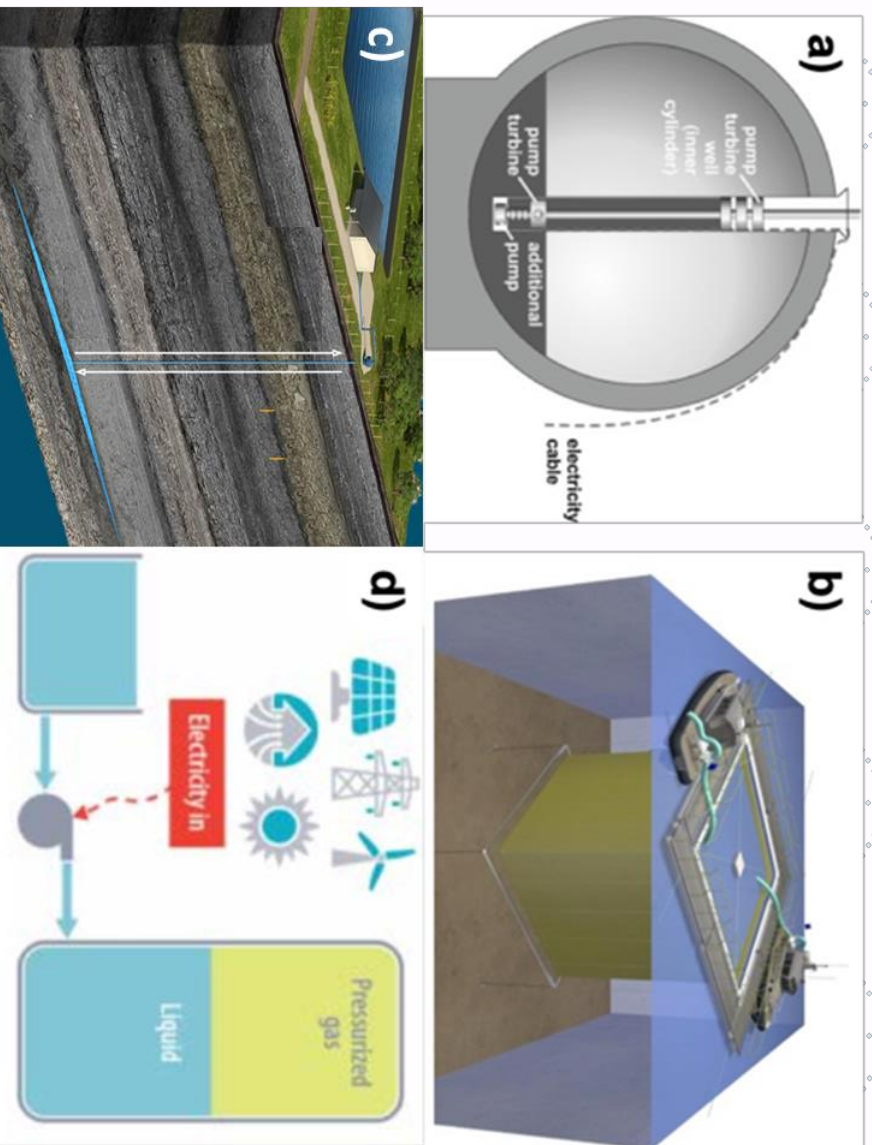
Huge initial cost, low average cost, matured tech, largest in the world



DOE global energy storage database. Available online: <http://www.energystorageexchange.org/projects> (accessed on 1 March 2016)

# Innovative Pumped Storage Hydropower

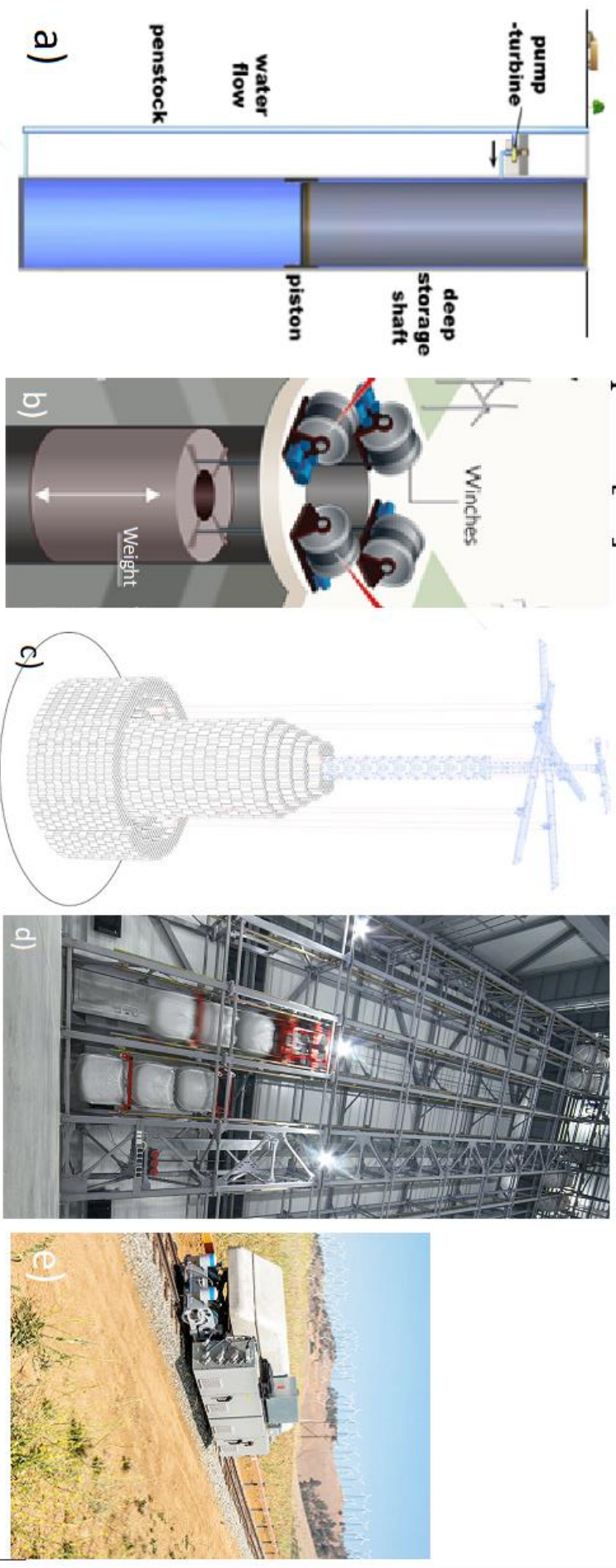
Modularity, less environment impact, lower land footprint



- a) Hahn H, Hau D, Dick C, Puchta M. Techno-economic assessment of a subsea energy storage technology for power balancing services. Energy 2017;133:121–7.
- b) Hadjerioua B, Eldredge T, Medina H, DeNeale S. Hydrodynamic and structural response modeling of a prototype floating membrane reservoir system for pumped storage hydropower. Journal of Hydraulic Engineering 2019;145:4019032.
- c) Quidnet Energy
- d) Odukomaia A, Abu-Heiba A, Graham S, Women AM. Experimental and analytical evaluation of a hydro-pneumatic compressed-air Ground-level Integrated Diverse Energy Storage (GLIDES) system. Applied Energy 2018;221:75–85.

# Gravity Energy storage beyond water

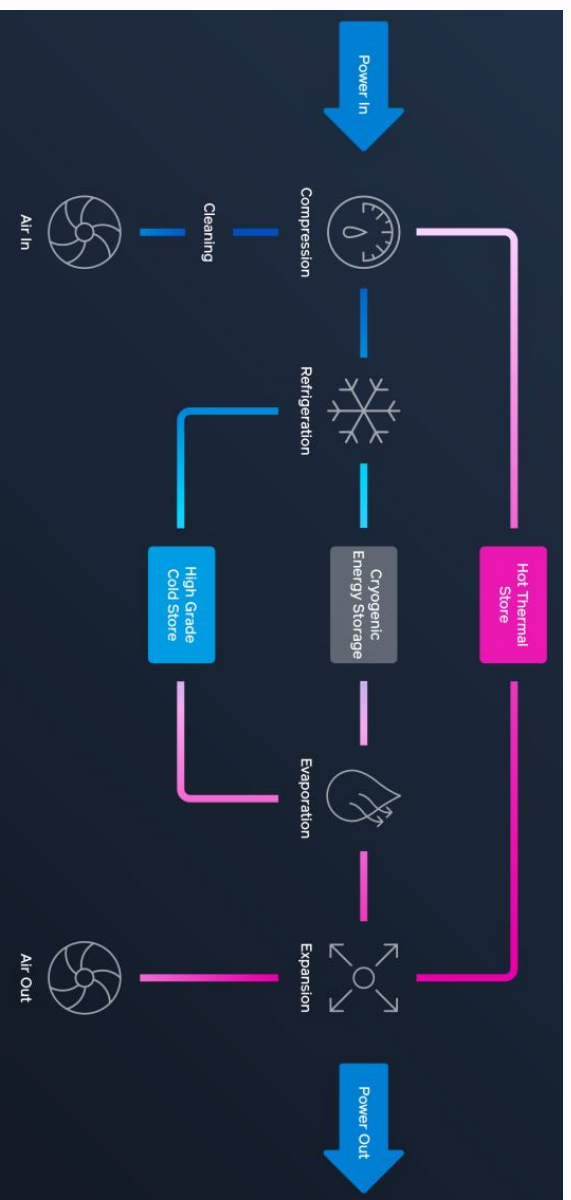
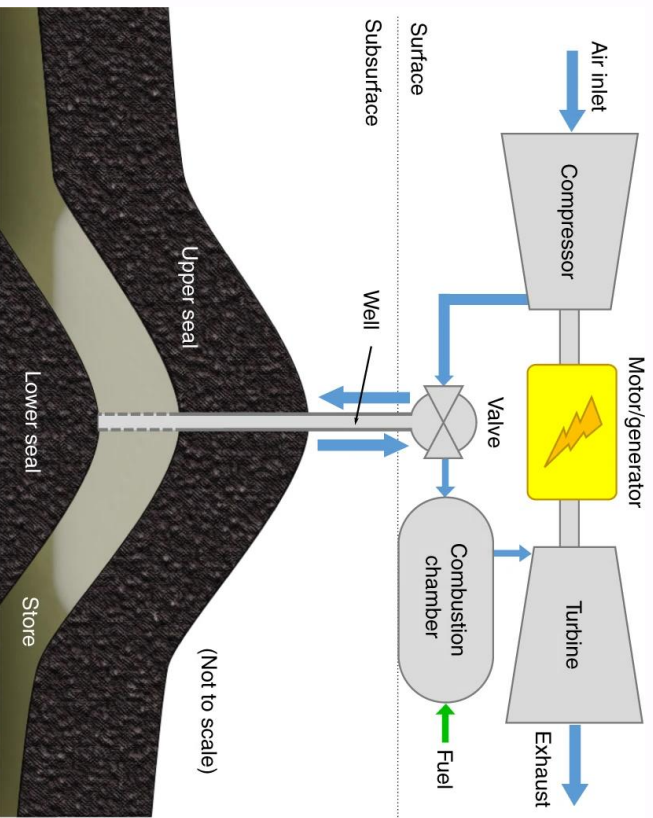
Site flexibility, land footprint, oil & gas well, recycle materials



- Gravity Power Inc. Technology - Gravity Energy Storage. Official Website 2017. <http://www.gravitypower.net/technology-gravity-power-energy-storage/> (accessed March 12, 2021).
- Gravitricity. Fast, long-life energy storage - Gravity energy storage system | Gravitricity technology 2020. <https://gravitricity.com/technology/> (accessed March 12, 2021).
- Fyke A. The fall and rise of gravity storage technologies. *Joule* 2019;3:625–30.
- ARES. ARES Nevada Project. ARES 2019. <https://aresnorthamerica.com/nevada-project/> (accessed June 12, 2021).
- Cava F, Kelly J, Peitzke W, Brown M, Sullivan S. Advanced rail energy storage: green energy storage for green energy. *Storing Energy*. Elsevier; 2016, p. 69–86

# Compressed Air Energy Storage

Mine utilization, heat integration, high maturity, site flexibility

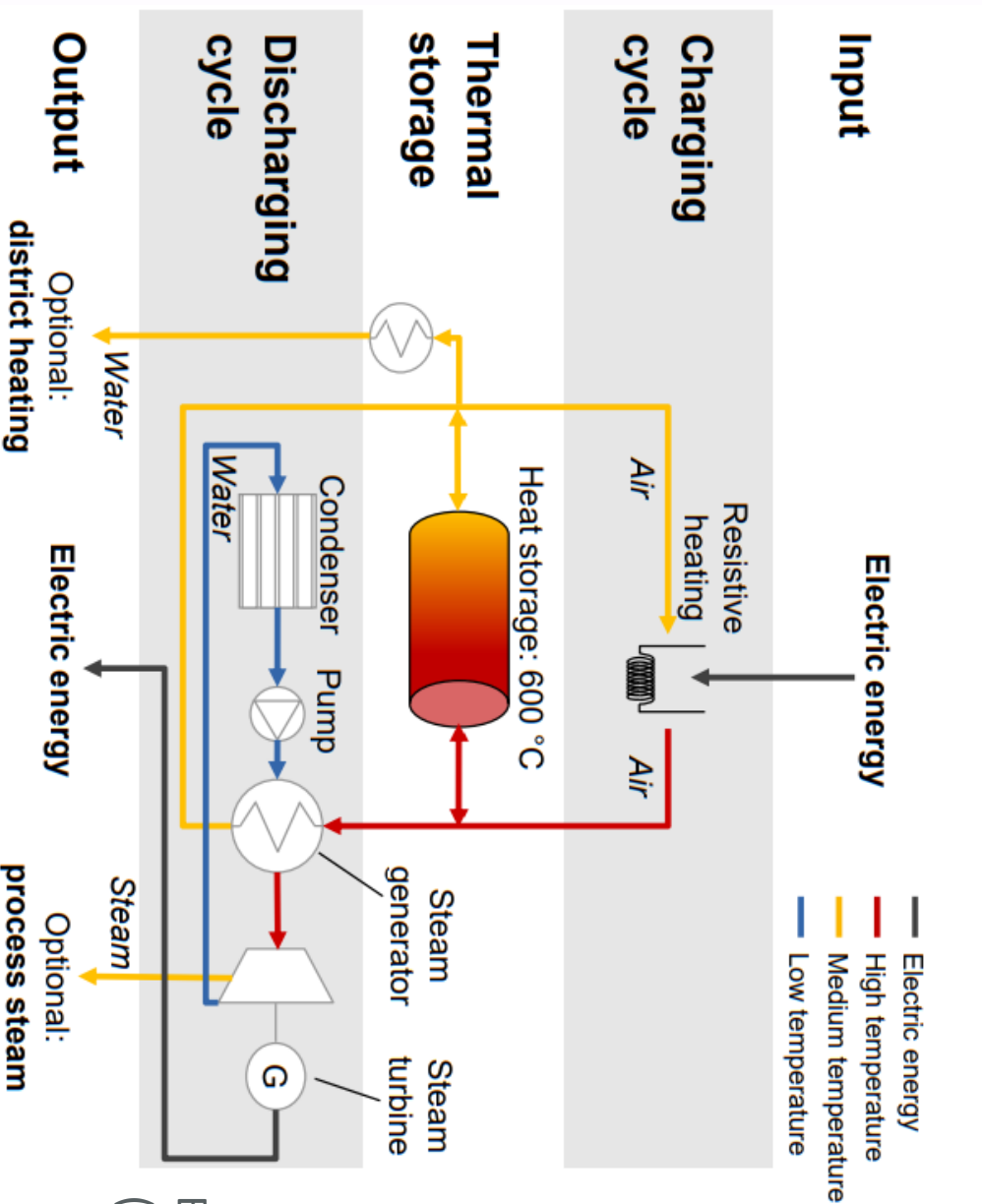


Mouli-Castillo, J., Wilkinson, M., Mignard, D., McDermott, C., Haszeldine, R. S., & Shipton, Z. K. (2019). Inter-seasonal compressed-air energy storage using saline aquifers. *Nature Energy*, 4(2), 131-139.

Technology | Highview Power <https://highviewpower.com/technology/>

# Thermal Storage

Heat integration, some subtype matured, scalability, low efficiency



Electric Thermal Energy Storage (ETES) Process diagram, Siemens

# Flow battery

Small land footprint, scalable, various technologies

1. Zinc:
  1.  $\text{Zn} + \text{O}_2 \rightarrow \text{ZnO}$  (Zinc8)
  2.  $\text{Zn} + \text{Br}_2 \rightarrow \text{ZnBr}_2$  (Gellion Endure)
2. Vanadium:
  1.  $\text{VO}_2^{2+} + \text{V}^{3+} \rightarrow \text{VO}_2^{+} + \text{V}^{2+}$  (Invinity)
3. Sulfur:
  1.  $\text{S}_2^{2-} \rightarrow \text{S}_4^{2-}$  (Form Energy)
4. Iron:
  1.  $\text{Fe} + \text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$  (EES, Form Energy)

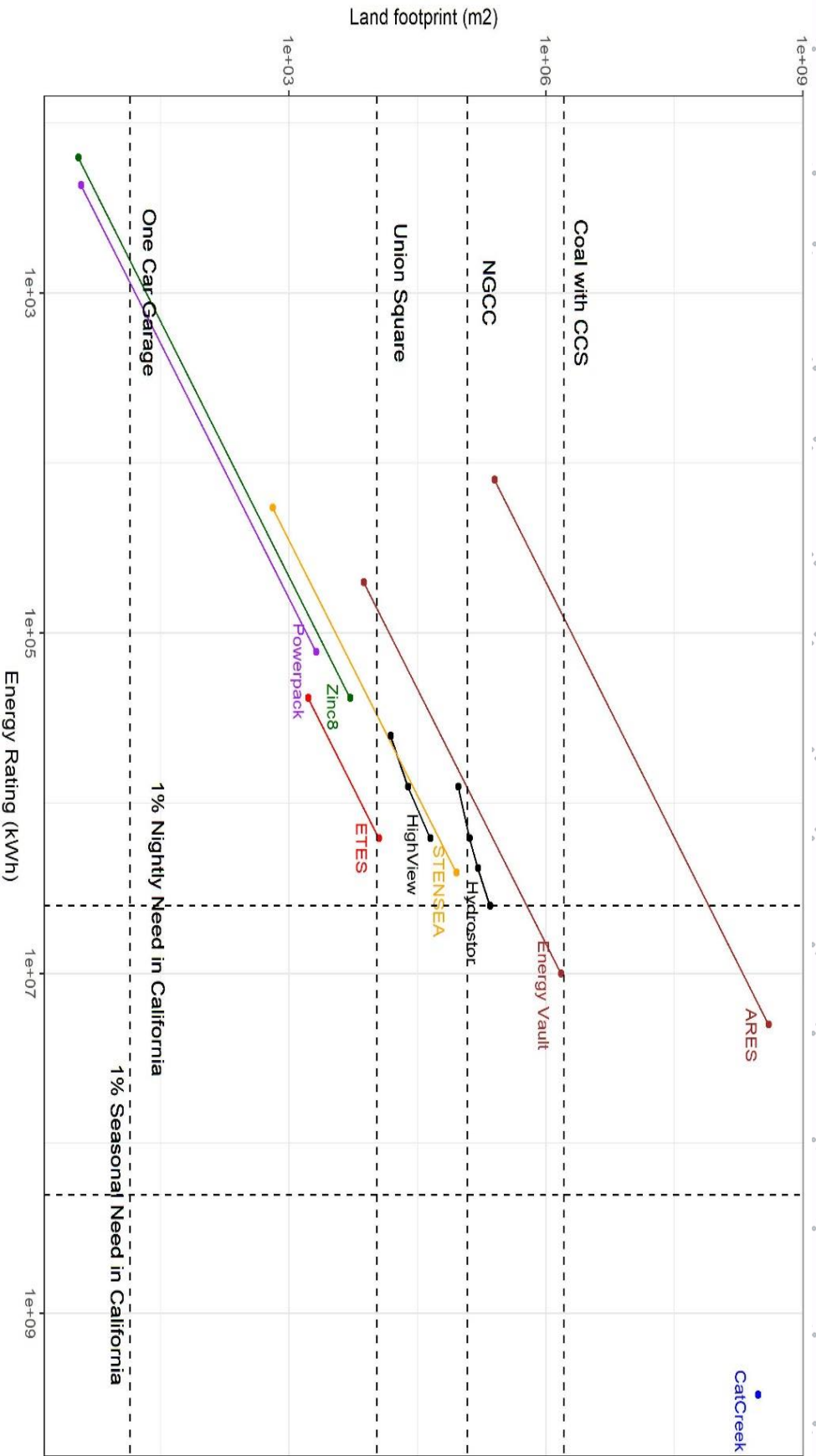
\*chemical equations are illustrative but not indicate the company adopt the exact configuration



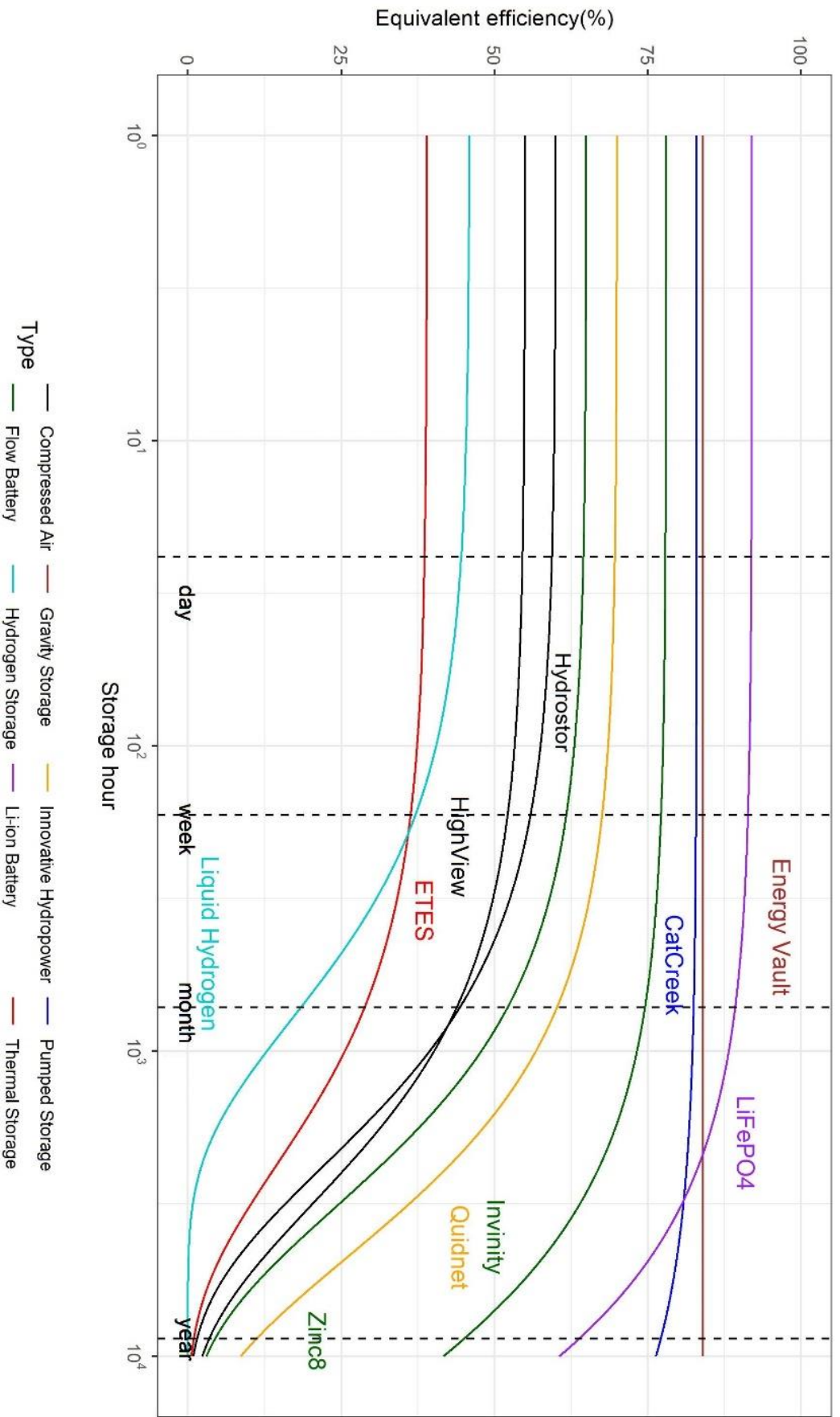
# Technology Comparison

Land footprint, efficiency and cost

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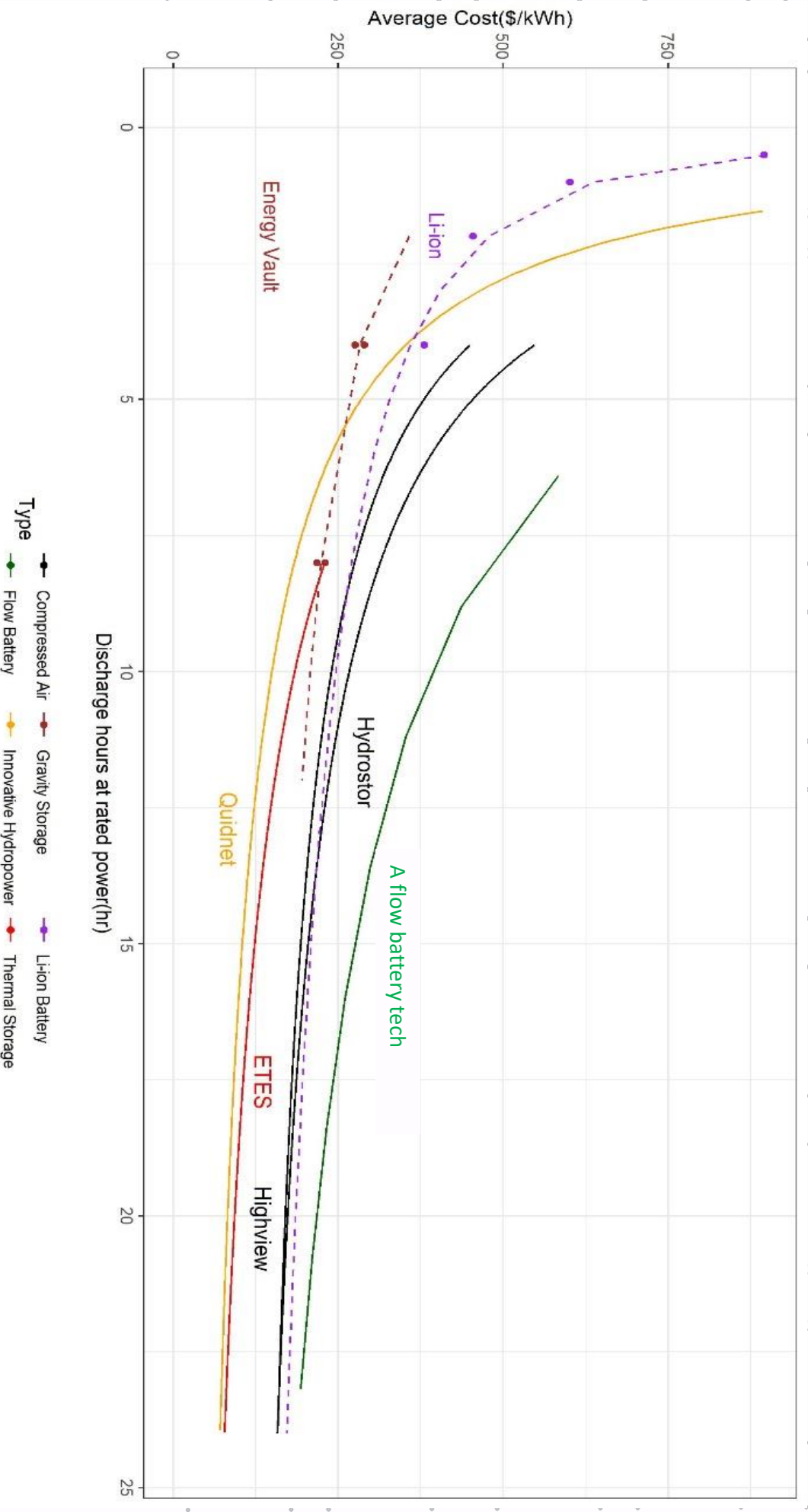


# Land footprint



# Equivalent Efficiency

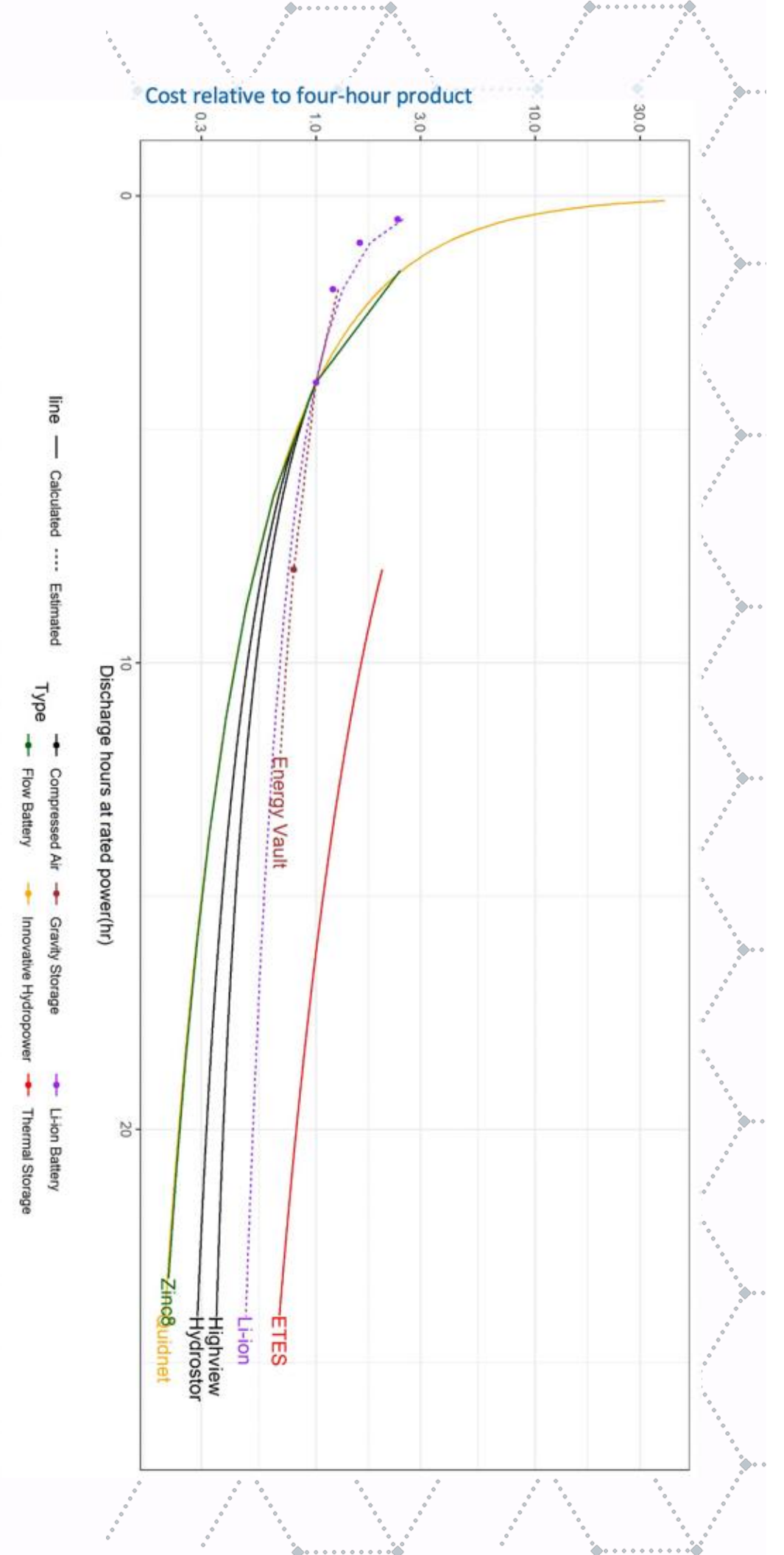
*Equivalent efficiency (x) = Round trip efficiency × (1 – idle loss per hour)<sup>x</sup>*



# Average Capital Cost

$$C_x = \frac{E_r \times C_r + (E_x - E_r) \times C_{mar}}{E_x}, \text{ They may have different power ratings}$$

Asymptote indicates the marginal energy cost



# Average Capital Cost

Standardized by 4-hour

# Conclusion

Usage	PSH	Gravity	Flow Battery	Thermal	Compressed Air
Retrofit/Integration with Thermal plant	X	X	X	V	V
Residential	X	X	V	X	X
Commercial/Industrial / Small-medium Utility	X	V	V	V	V
Regional/Large Utility	V	V	X	X	V

**Brown** indicates applicable for seasonal and resilience usage

V/X indicates applicable for certain use cases

Desired energy and power ratings are necessary for cost comparison



THANK YOU

Q&A