The Electrification Strategy

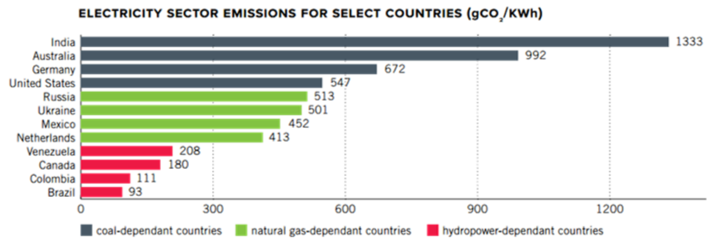
"The most plausible way to reduce global CO_2 emissions is … to increase the role of very low carbon technologies in electricity generation and to increase the use of electricity in transportation and heating."

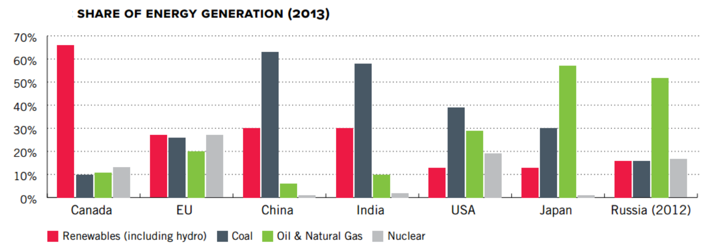
Schmalensee, Energy Economics, 52 (2015)

"…there is no single technology that can be said to be the cheapest under all circumstances.
[…] system costs, market structure, policy environment and resource endowment all continue to play an important role in determining the [value] of any given investment."

IEA, Projected Costs of Generating Electricity 2015 edition

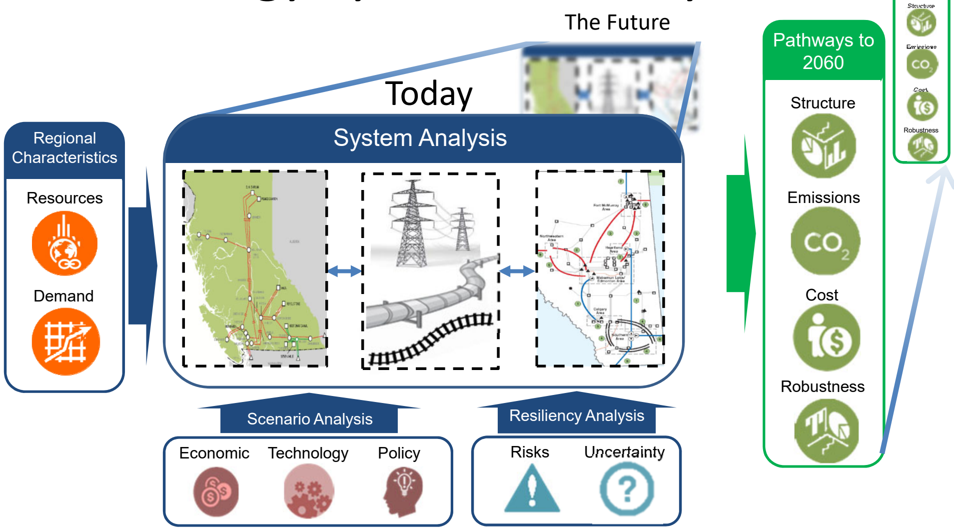
Canada’s Advantage





Of course it will work…

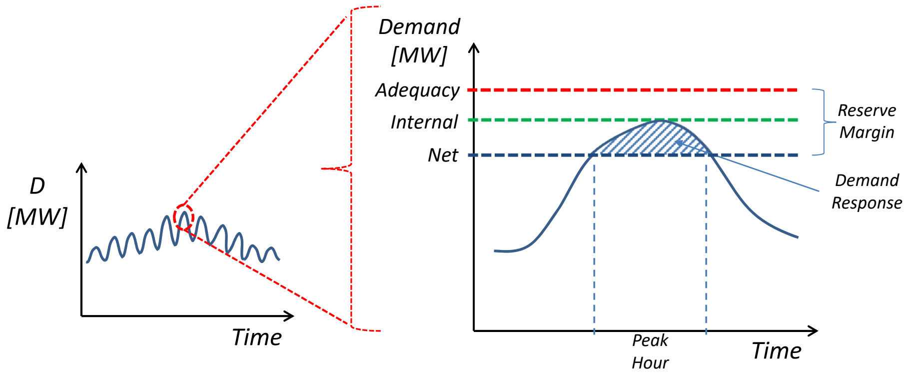
Energy System Pathways



Electricity System 101

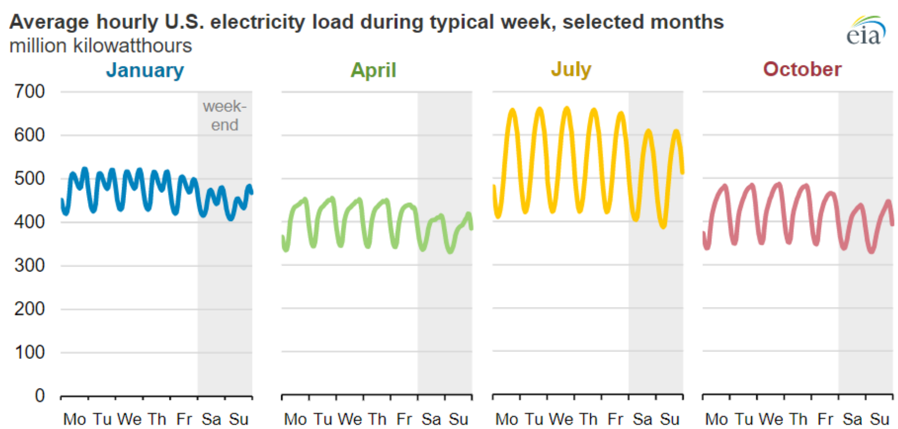
Electricity Demand

- What is at the end of the line and how does it behave?



FEBRUARY 21, 2020

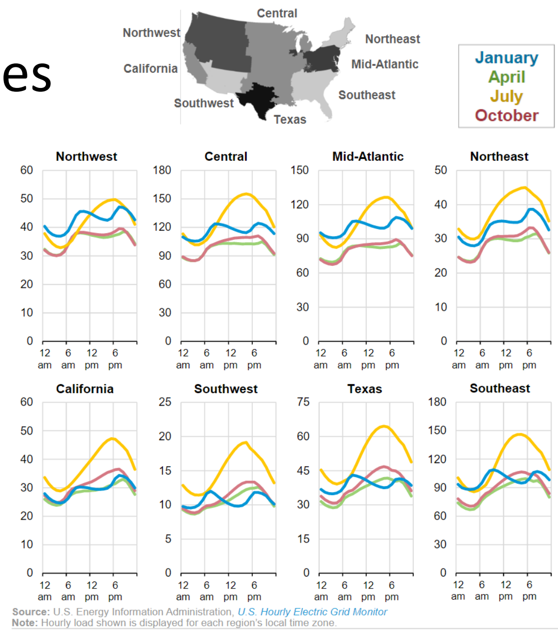
Hourly electricity consumption varies throughout the day and across seasons



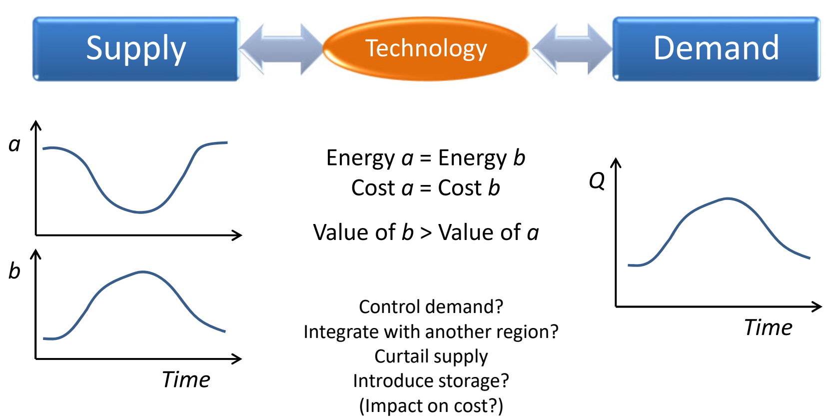
Source: U.S. Energy Information Administration, *U.S. Hourly Electric Grid Monitor*
Note: Data shown represent the average aggregate U.S. hourly load (Eastern Standard Time) by day of the week for the months indicated between 2015 and 2019.

Regional Demand Profiles

- Air-conditioning equipment is used in 87% of homes in the United States.
- The daily U.S. load cycle in the summer has a much wider range than in the winter because of the widespread use of air conditioning.

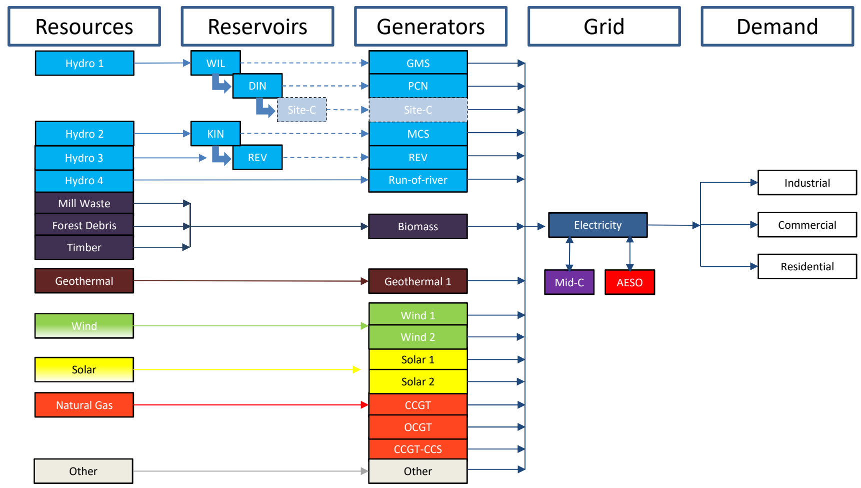


The Goal – instantaneous supply matching demand

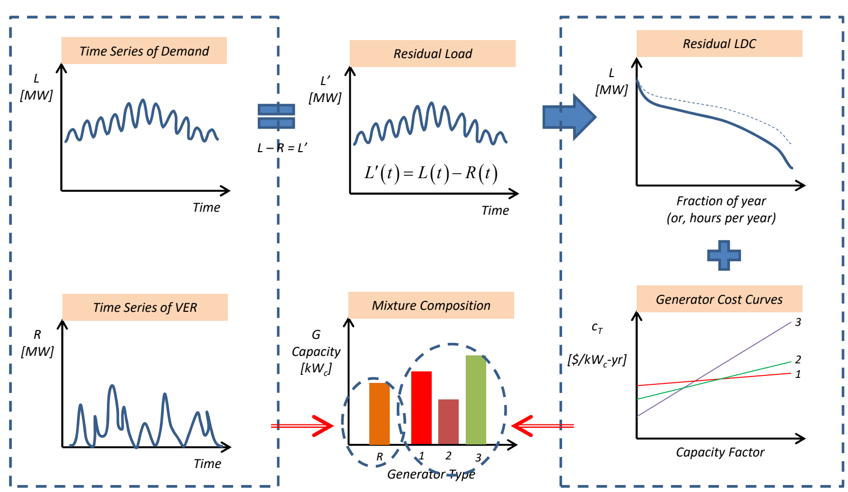


- How does the addition of one option affect the entire system?

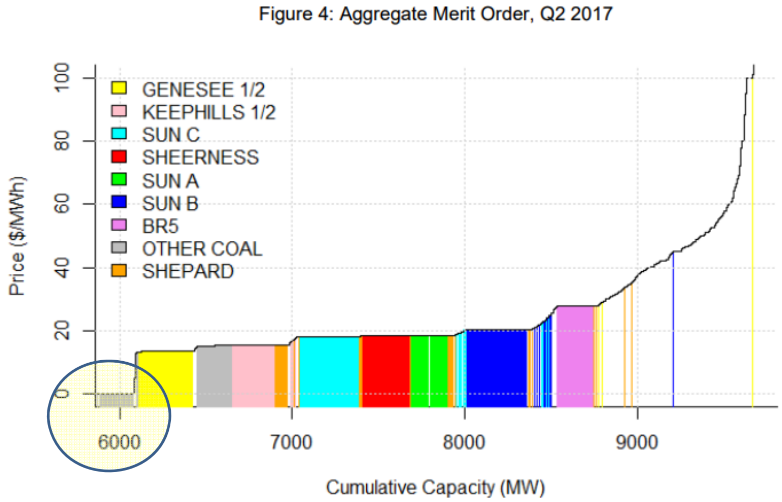
Low Carbon Supply Options to Serve Demand



Long-term mixture planning with variable energy resources (VER)

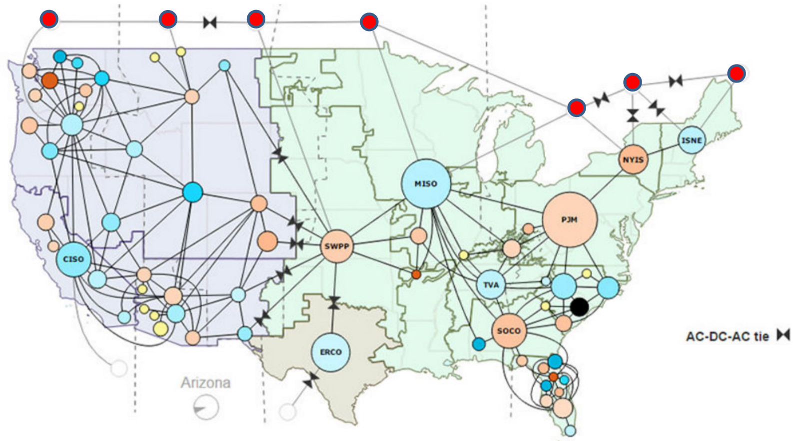


Alberta (AESO) Electrical Supply



MSA 2017 Second Quarter Report https://albertamsa.ca/index.php?page=quarterly-reports

Transmission and Interconnections

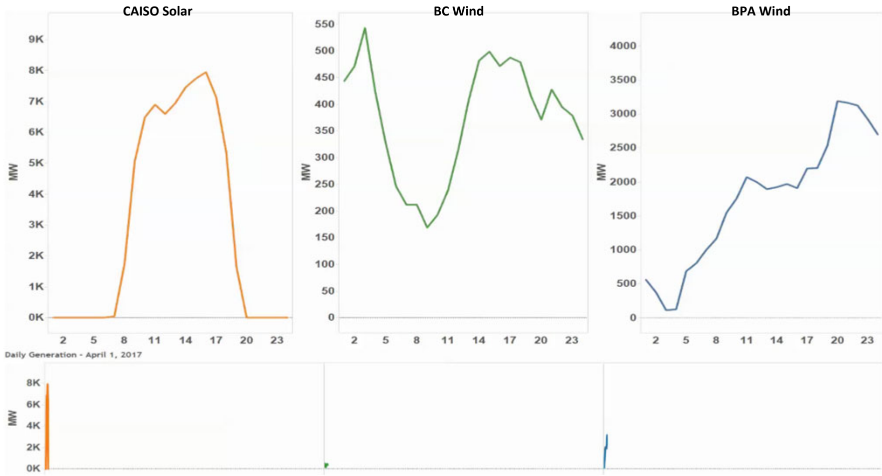


http://www.eia.gov/beta/realtime_grid/#/summary/about?end=20160724&start=20160625&regions=01

Electrification Step 1 – decarbonize generation

Renewable Resources - Variability

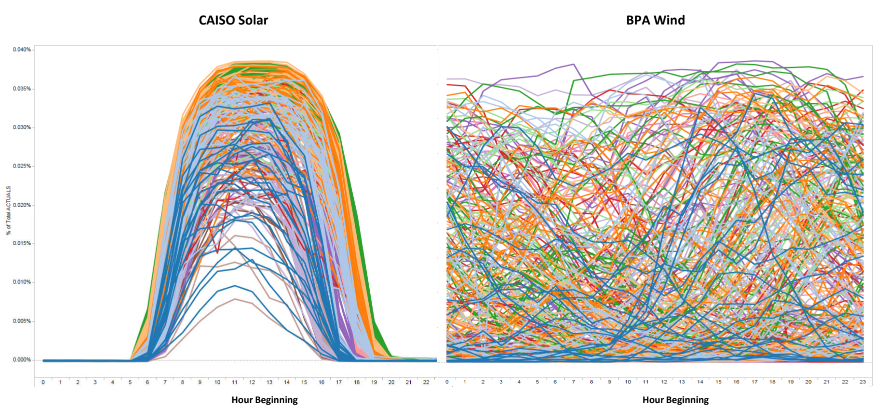
(April 1, 2017 – May 30, 2017 - Video)



Courtesy of POWEREX

Solar vs. Wind Generation – One Year

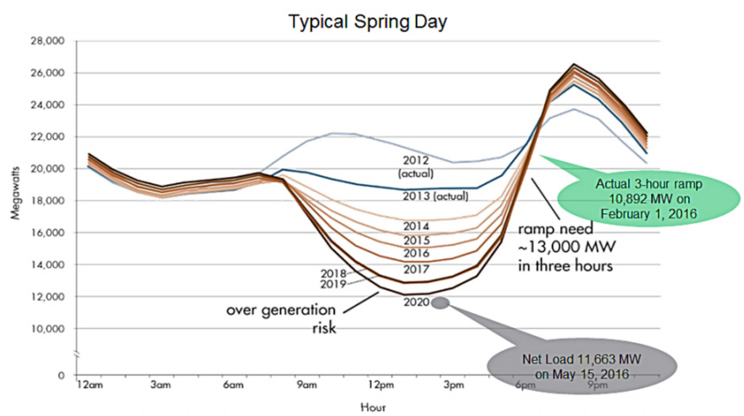
Each line represents one day, line colors by month, Feb 8, 2017 – Feb 8, 2018



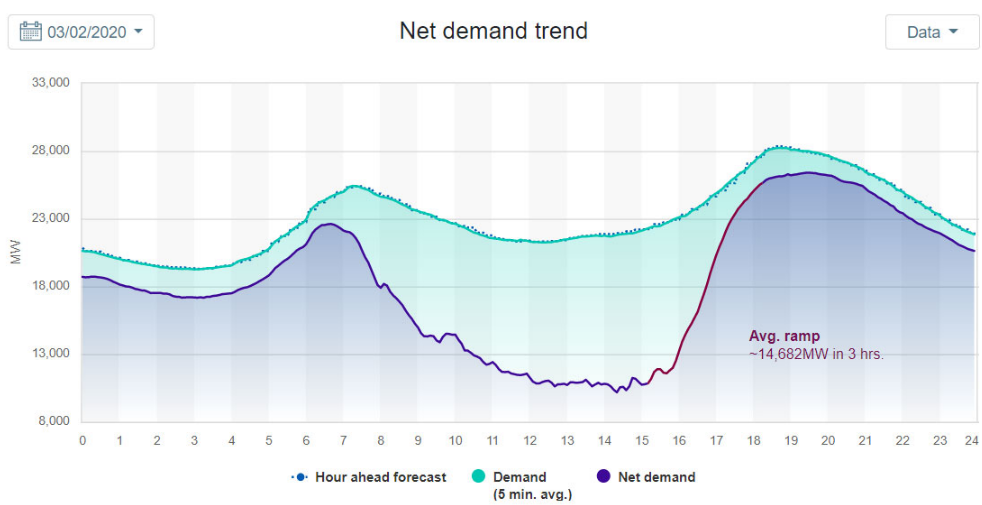
Courtesy of POWEREX

Aggregated Effect on System

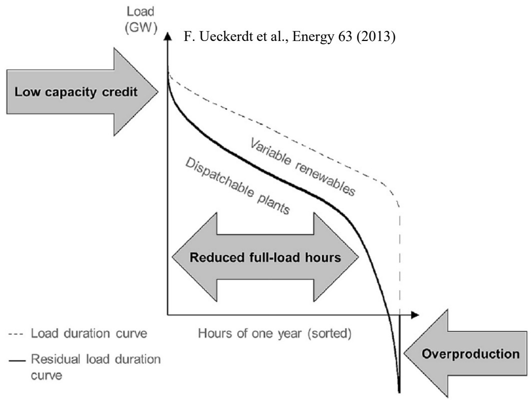
Figure 2: The duck curve shows steep ramping needs and overgeneration risk



CAISO -demand minus solar and wind

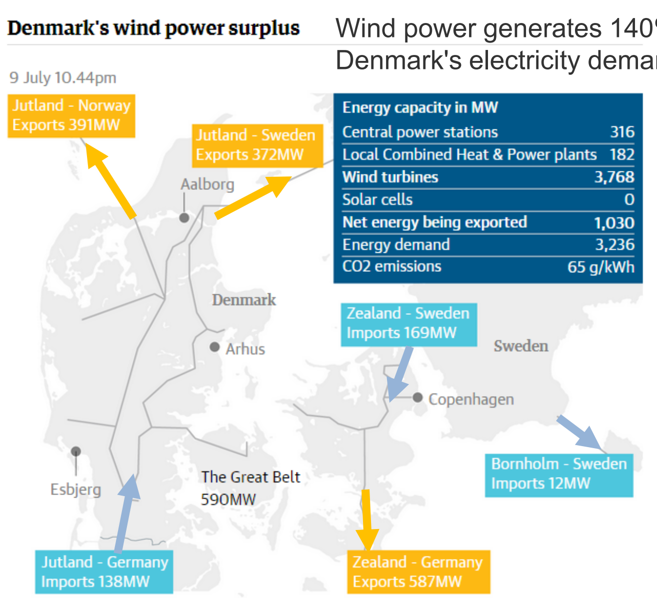


Challenges of large VER additions

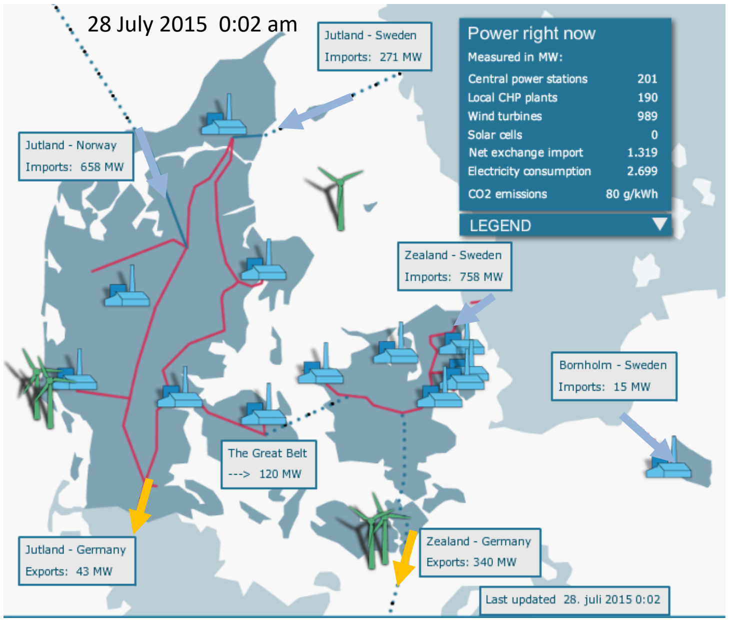


- Low capacity credit, cannot reduce conventional capacity
- Baseload hours reduced – low cost generation hours
- Excess supply – curtailment, negative prices

Wind power generates 140% of Denmark's electricity demand



<http://www.theguardian.com/environment/2015/jul/10/denmark-wind-windfarm-power-exceed-electricity-demand>



Imports are 50% of Denmark's electricity demand

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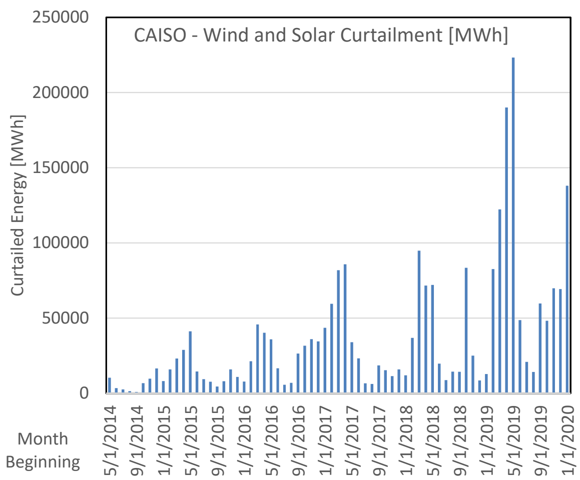
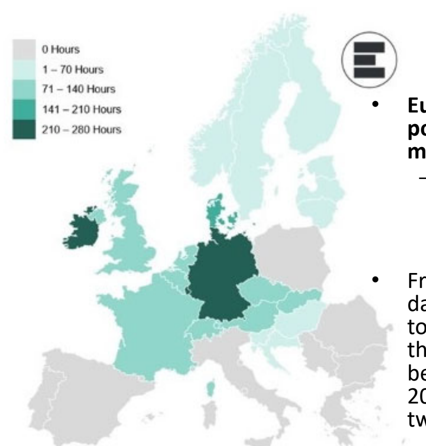
Curtailment and Negative Electricity Prices





The total number of hours of negative day ahead prices in the markets in 2020.

- **Europe negative power prices first nine months of 2020,**
  - excess power in the market resulting in consumers being paid rather than charged to use electricity.
- Frequency of negative day-ahead prices three to four times higher than those seen between 2015 and 2018, and more than twice those in 2019.

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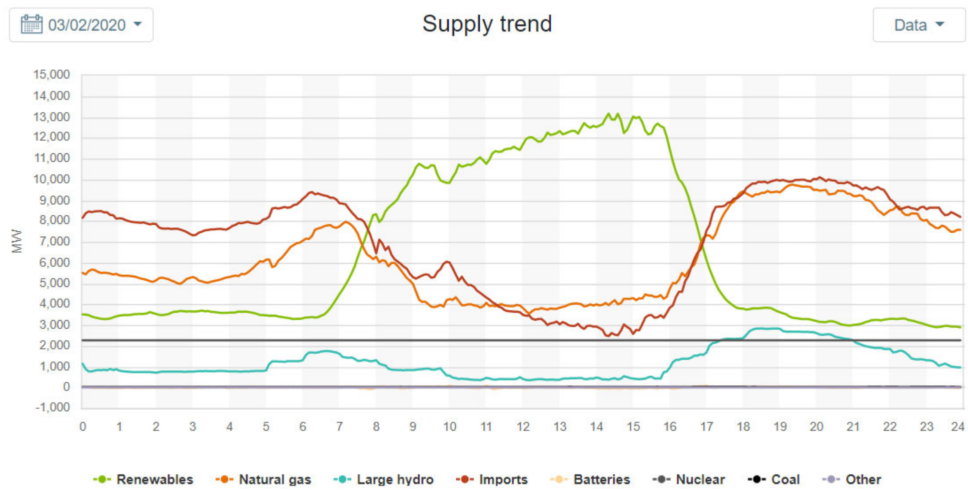
CAISO – supply and flexibility



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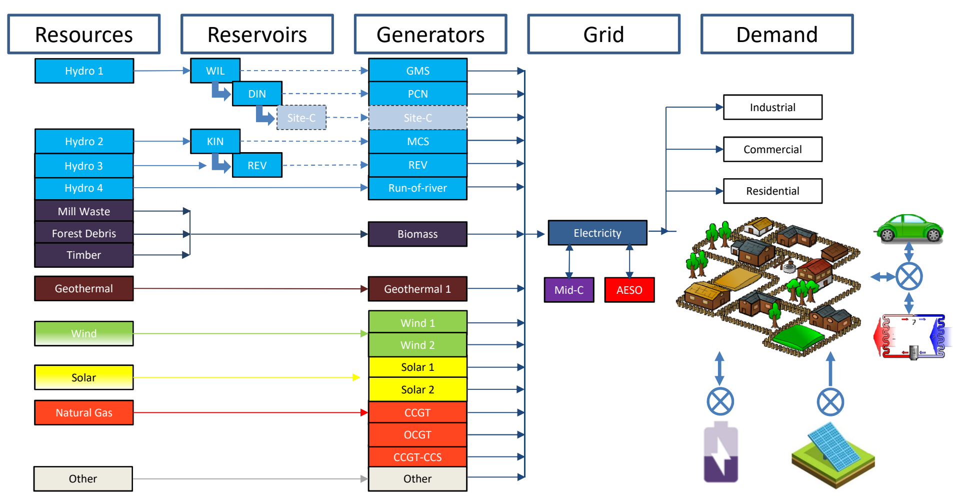
Electrification Step 2 – Shift Service Technologies



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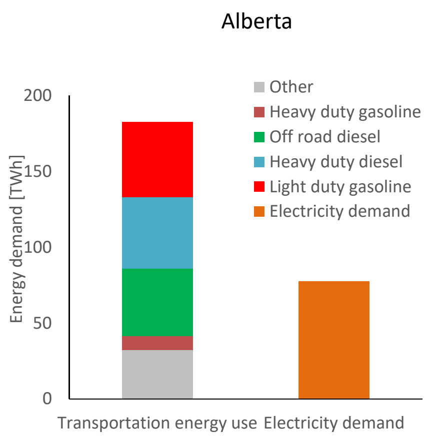
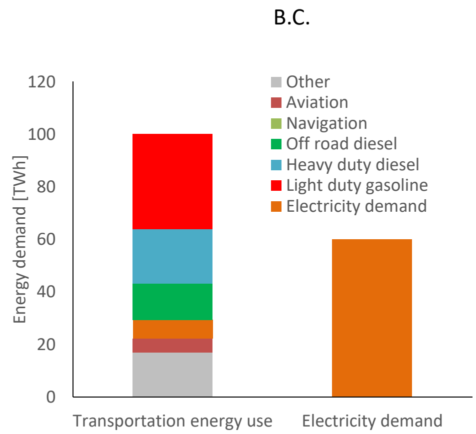
2013 Secondary Energy

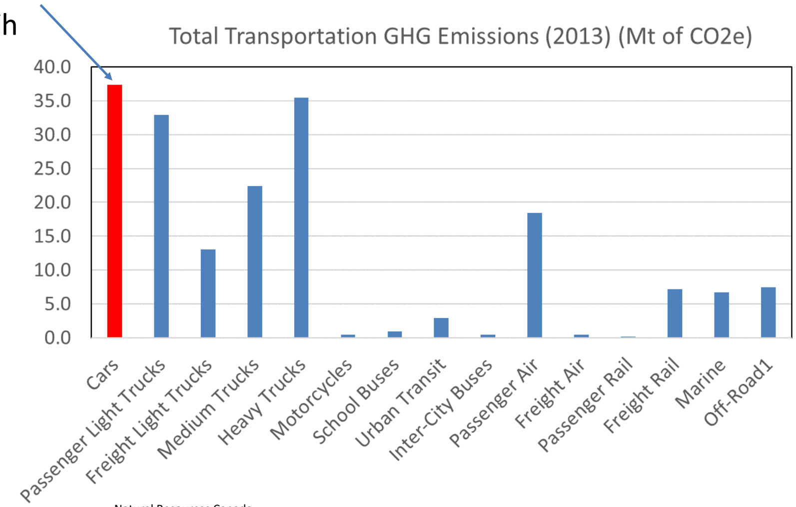




[20] http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=tran&juris=ca&rn=8&page=0

Electrified Demand ~50 TWh

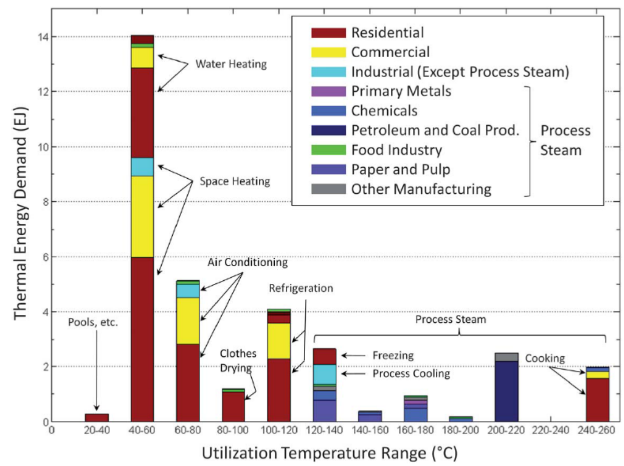
Transportation in Canada



Natural Resources Canada

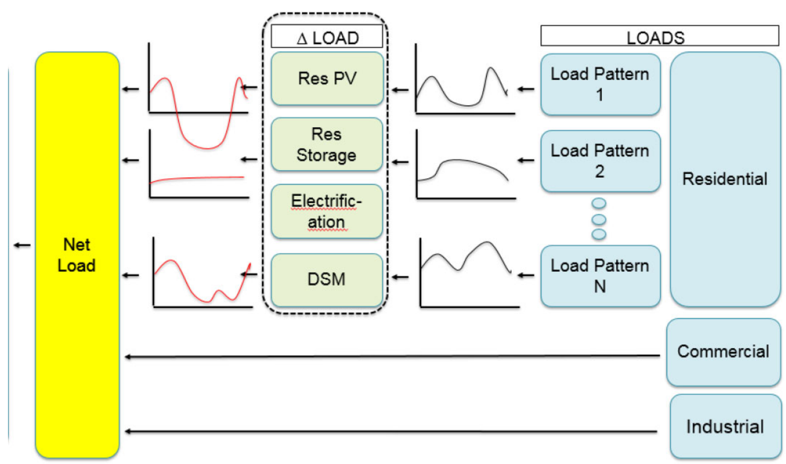
Electrifying Heat – Energy Demand

- US Heat Demand
  - equivalent ~50% of other electrical demand.
- End-use technology efficiencies could make electrical demand similar to current electrical demand.
- Temporal patterns make the required electrical capacity much higher.

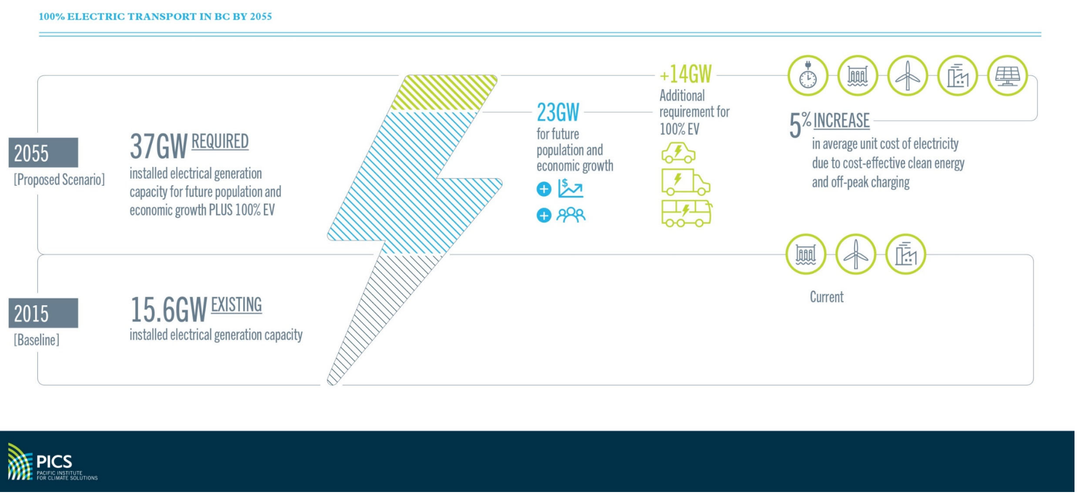


D. B. Fox et al., Energy and Environmental Science, Issue 10, 2011.

Future Electricity Demand



Capacity, Energy, Flexibility



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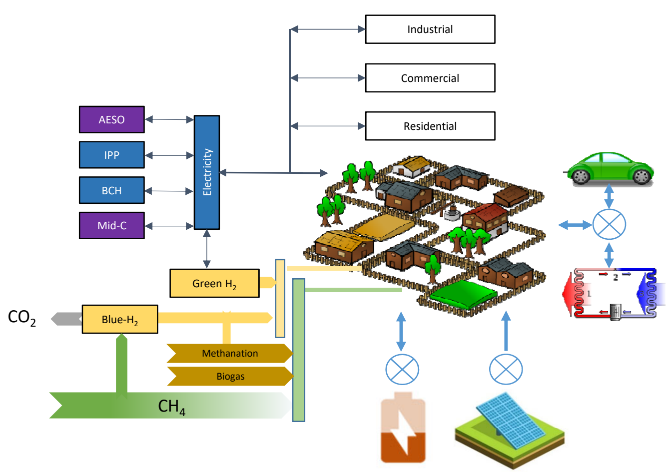
Electrification Step 3 – gas and chemical fuels



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Electrification Step 4 – make it work

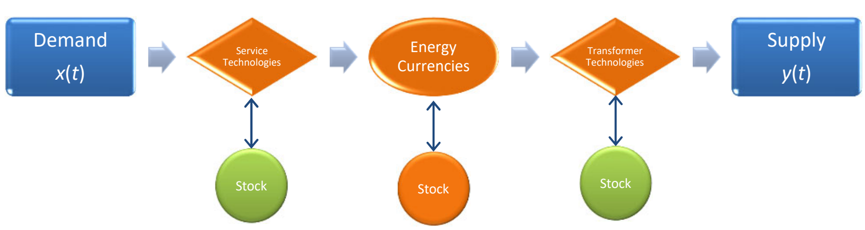
- Control Supply
  - curtail
  - excess capacity
  - dispatchability
  - flexibility
- Control Demand
  - constrained resource, uncertain
  - acceptance?
- Trade
  - use transmission system
- Storage

Decarbonization Pathways – Electrification and Storage Part II

Living Without Oil Seminar Series

Andrew Rowe

The Energy System Architecture



- Stored sources allow temporal and spatial decoupling between steps in energy chain
  - Storage always there, but somewhat hidden as Nature has taken care of this for us…
  - Now want to use dynamic sources
- Spatial and temporal connections as well as transformations

Where can we get flexibility?

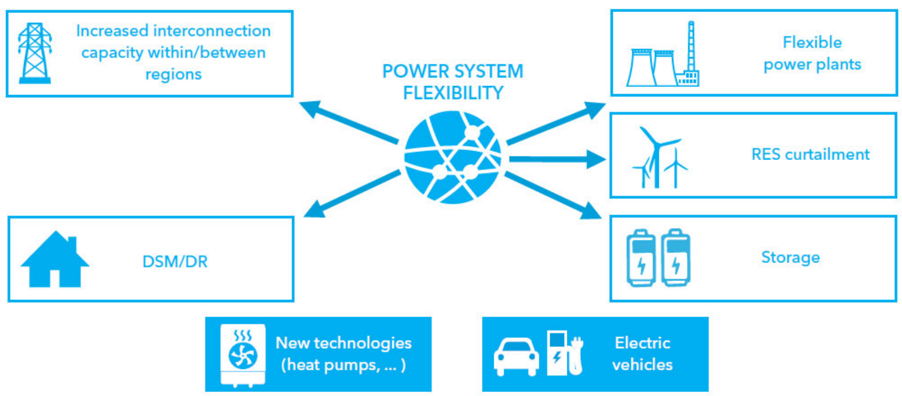
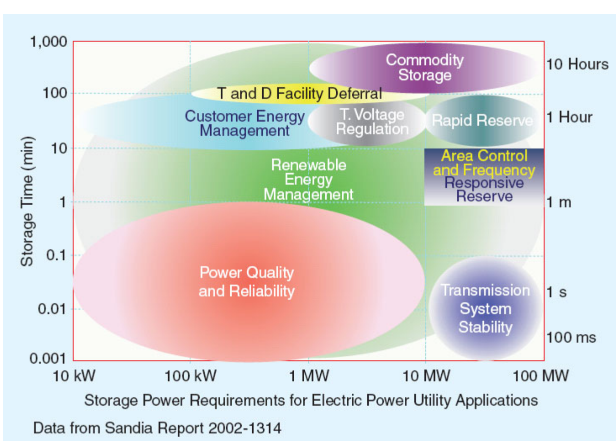
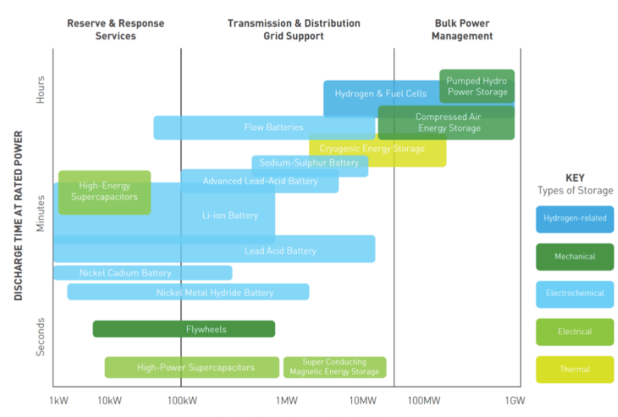


Figure 14 - Flexibility options in the power system

DNV GL White Paper 2017, Flexibility in the Power System

Grid Storage



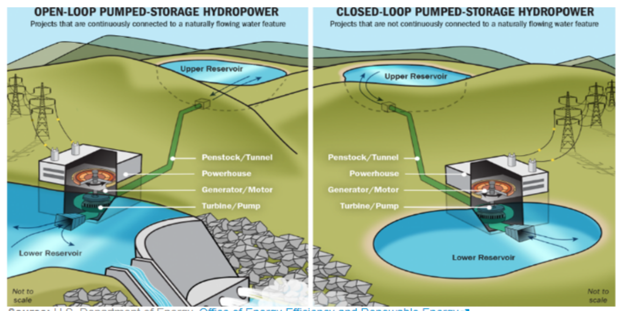


Ali Nourai and Chris Schafer, IEEE Power and Energy Magazine, Jul 2009

Pumped Hydro

- Efficiency includes both conversion efficiency and storage losses.
  - Storage losses due to evaporation and seepage
  - Most modern PHS plants operate with round trip efficiencies of 75–80%
- Ideal PHS sites are often well away from load centers
  - resulting in transmission losses.

Pumped storage hydropower systems are generally one of two types. An open-loop system has a continuous source of downstream water that is pumped uphill to an upper storage reservoir. Typically, an open-loop plant pumps water that has already passed through the dam up to the storage reservoir above the dam. By contrast, closed-loop systems pump water from a lower storage reservoir, which is not continuously filled with water and is generally not connected to a flowing source.



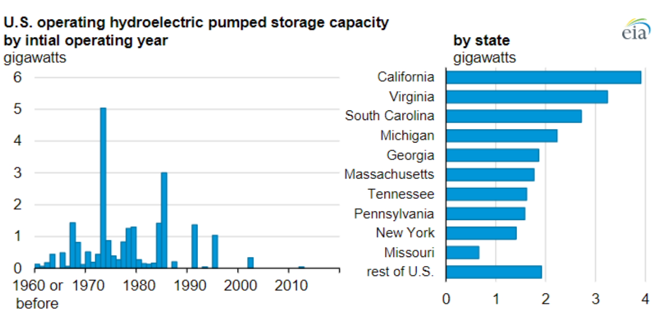
Source: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy

Historically, most U.S. pumped storage plants were installed on rivers as open-loop systems. However, more of the recent applications filed with the Federal Energy Regulatory Commission (FERC) for pumped storage hydro project licenses have been for closed-loop plants. One reason for the increase in closed-loop plants is that they capture streams of runoff water from agricultural irrigation systems that would otherwise go unused.

US Pumped Hydro

OCTOBER 31, 2019

Most pumped storage electricity generators in the U.S. were built in the 1970s



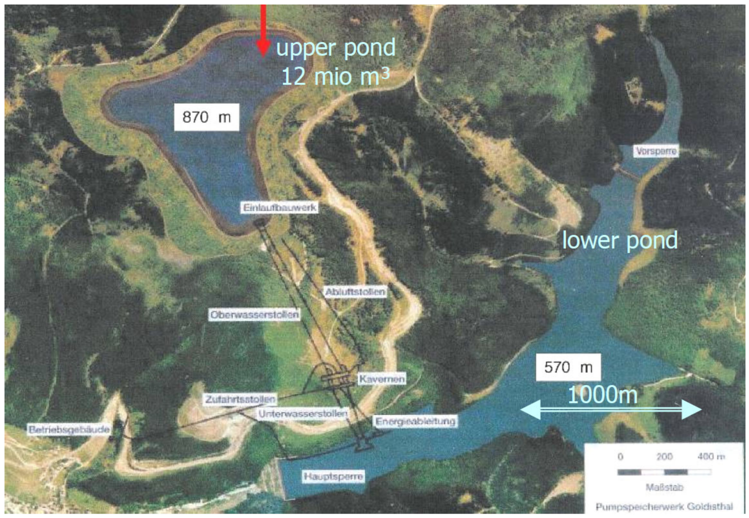
Source: U.S. Energy Information Administration, *Annual Electric Generator Report*

Table 1
Modern dedicated PHS facilities evaluated in this study

Facility	Location	Completion date	Power (MW)	Storage capacity (MWh)
Bad Creek	Salem, SC	1991	1000	24,000
Balsam Meadow	Shaver Lake, CA	1987	200	1600
Bath County	Warm Springs, VA	1985	Uprated ~~2100~~ 3000	23,100
Clarence Cannon	Center, MO	1984	31	279
Fairfield	Jenkinsville, SC	1978	512	4096
Helms	Shaver Lake, CA	1984	1206	184,000
Mt. Elbert	Leadville, CO	1981	200	2400
Raccoon Mtn.	Chattanooga, TN	1978	1530	32,130
Rocky Mtn.	Armuchee, GA	1995	760	6080

P. Denholm, G. Kulcinski, Energy Conversion and Management 45 (2000) 2153-2172

Pumped Hydro Storage



Brinkman, Eberle, Formanski, Matthe, “Vehicle Electrification – Quo Vadis”, GM Global R&D, April 2012

Pumped Hydro Storage

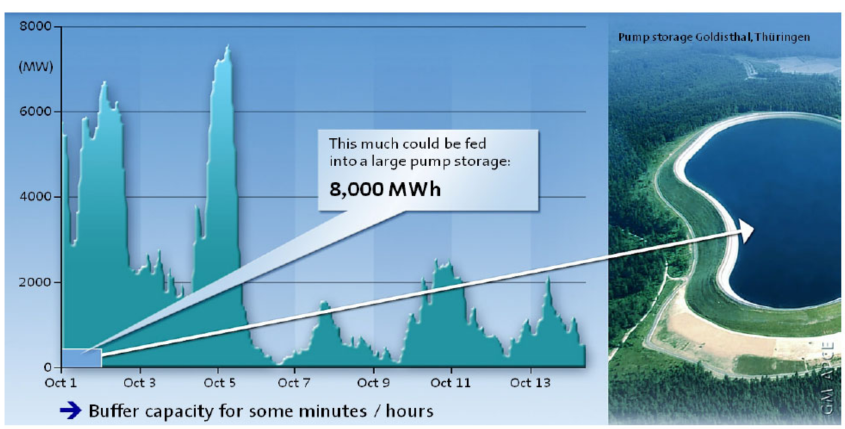
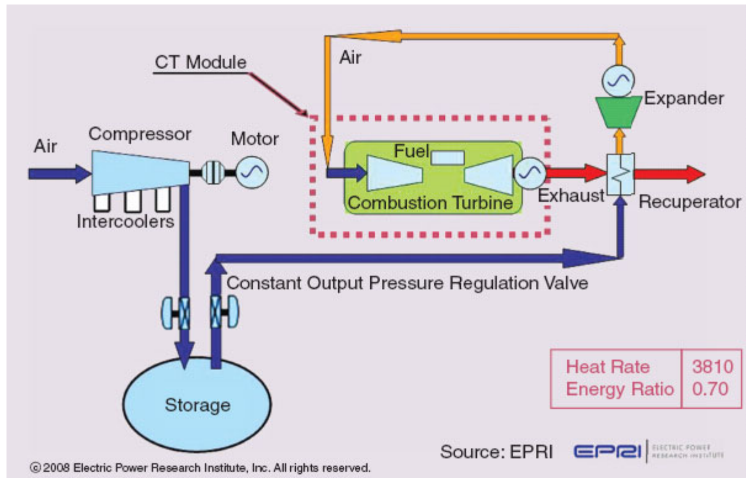


Figure 14 – Fluctuating wind energy in October 2008 in the grid operated by TenneT compared to biggest German pumped hydro storage Goldisthal (a Vattenfall installation in the state of Thuringia) [10].

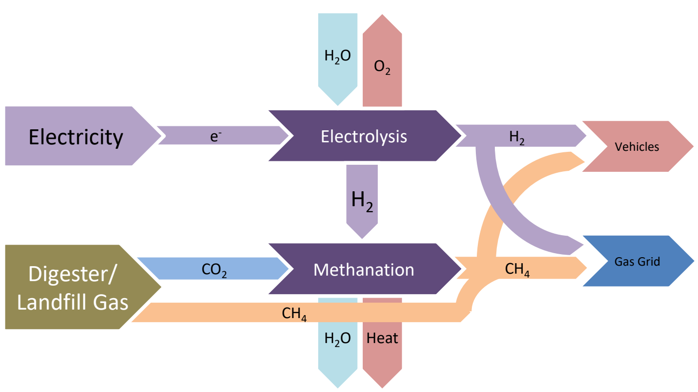
Brinkman, Eberle, Formanski, Matthe, “Vehicle Electrification – Quo Vadis”, GM Global R&D, April 2012

Compressed Air Energy Storage

- Consumes less than 40% of the gas used in a combined-cycle and 60% less gas than is used by a single-cycle gas turbine
- Can be in service in 15 min

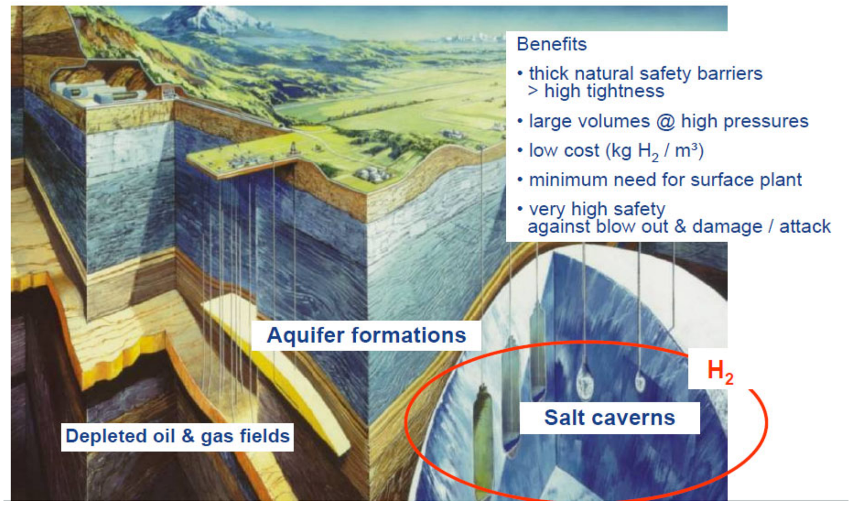


Power to Gas

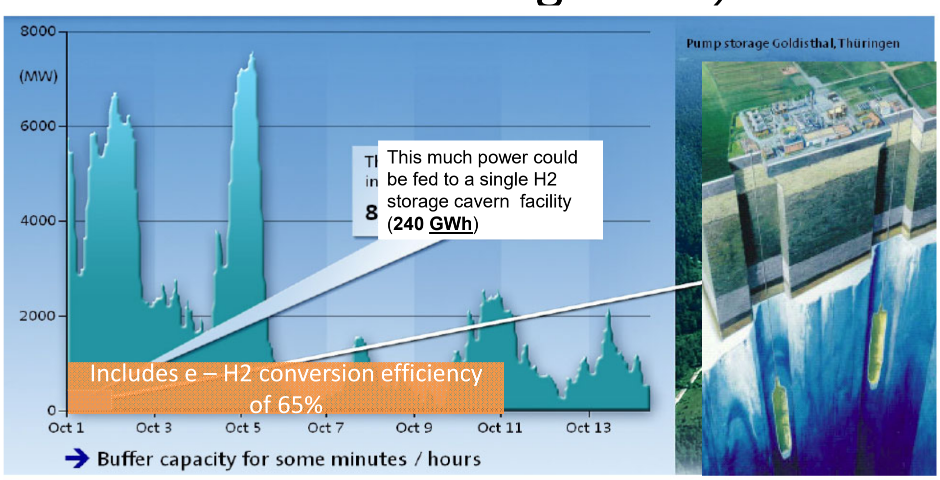


- Power to gas (P2G): make fuel and,
  a) inject H2 into NG system (up to 15% requires minimal changes)
  b) Methanization of H2 to CH4 – inject into NG system

Cavern Storage (CH_4, H_2, air)

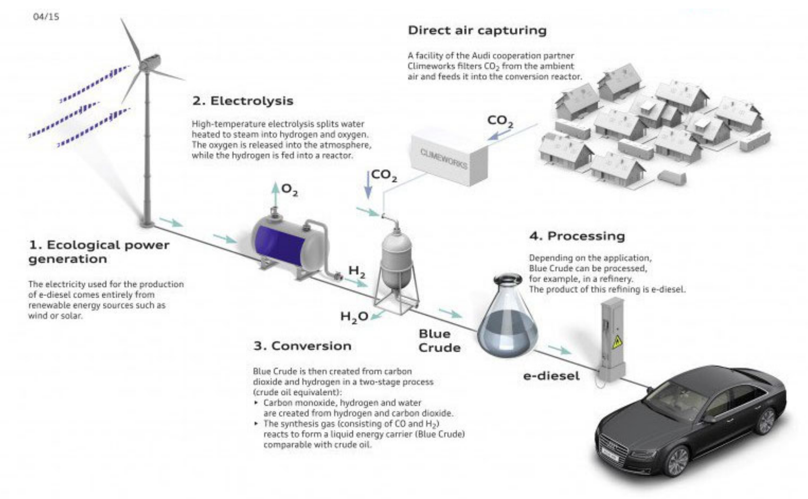


Cavern storage of H_2

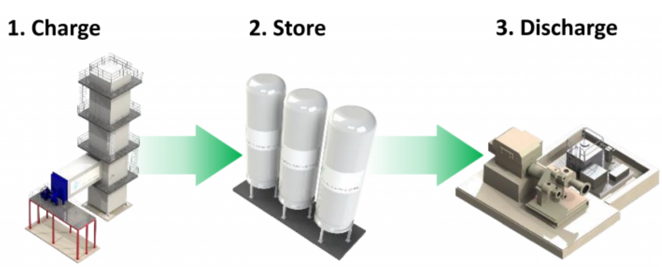


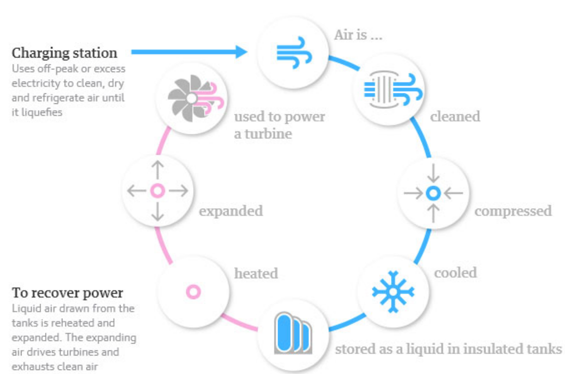
An average salt cavern can be charged at over 1 GW for 10 days. As of 2010 there were over 170 caverns in Germany (for natural gas.)

Power to Gas to fuel…



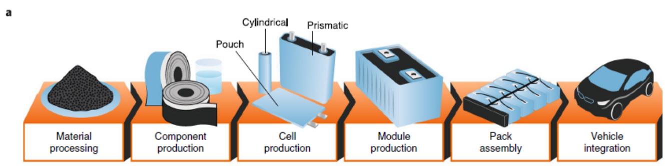
Liquid Air

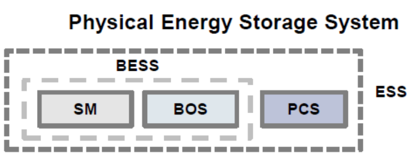




Stamatios et al., 2017 Applied Energy

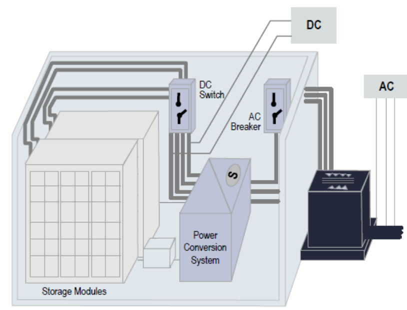
Electrochemical Batteries





Selected Equipment & Cost Components

System Layer		Component
SM	Storage Module	• Racking Frame/Cabinet • Battery Management System ("BMS") • Battery Modules
BOS	Balance of System	• Container • Monitors and Controls • Thermal Management • Fire Suppression
PCS	Power Conversion System	• Inverter • Protection (Switches, Breakers, etc.) • Energy Management System ("EMS")
EPC	Engineering, Procurement & Construction	• Project Management • Engineering Studies/Permitting • Site Preparation/Construction • Foundation/Mounting • Commissioning
Other (not included in analysis)		• SCADA • Shipping • Grid Integration Equipment • Metering • Land



Lazard 2018 Levelized Cost of Storage Analysis

Flow Batteries

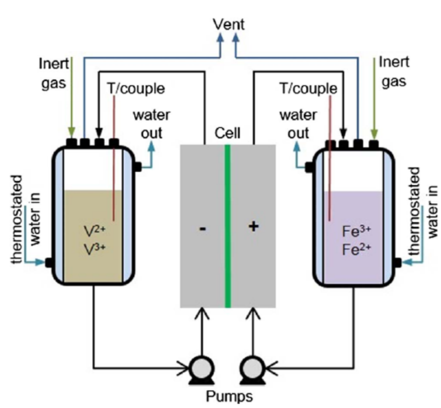
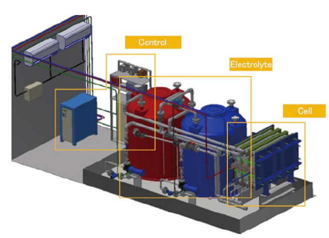
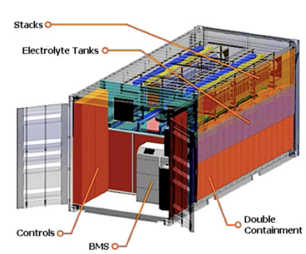


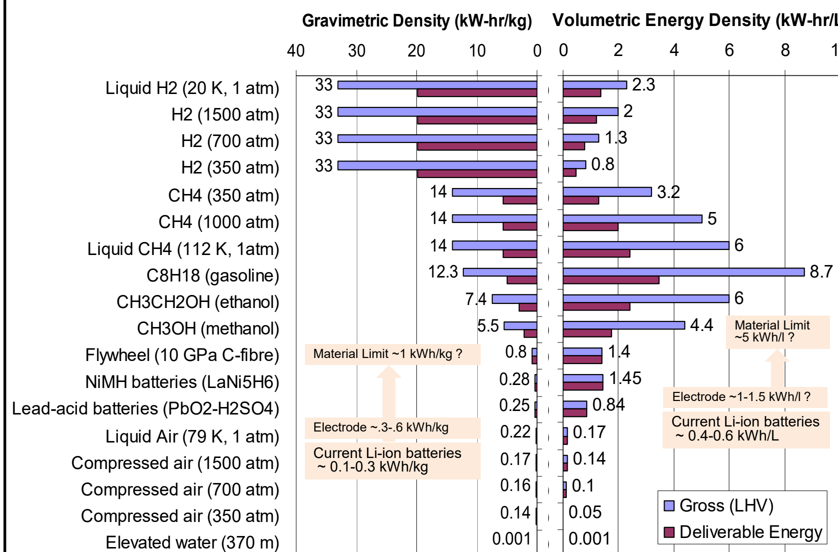
Fig. 1. Flow battery experimental setup.

Stamatios et al., 2017 Applied Energy

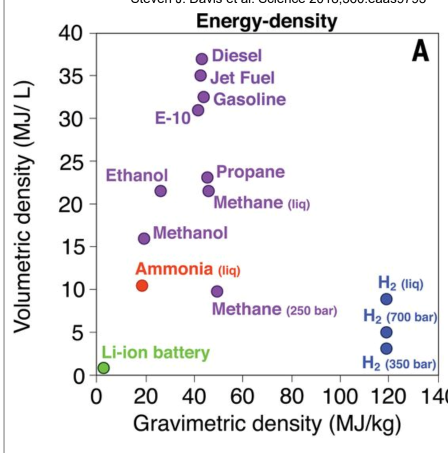




From Vanlon Energy Inc.



Steven J. Davis et al. Science 2018;360:eaas9793



Berry, G., et al, Hydrogen Storage and Transportation , Encyclopedia of Energy

Schmuch et al 2018, Nature Energy

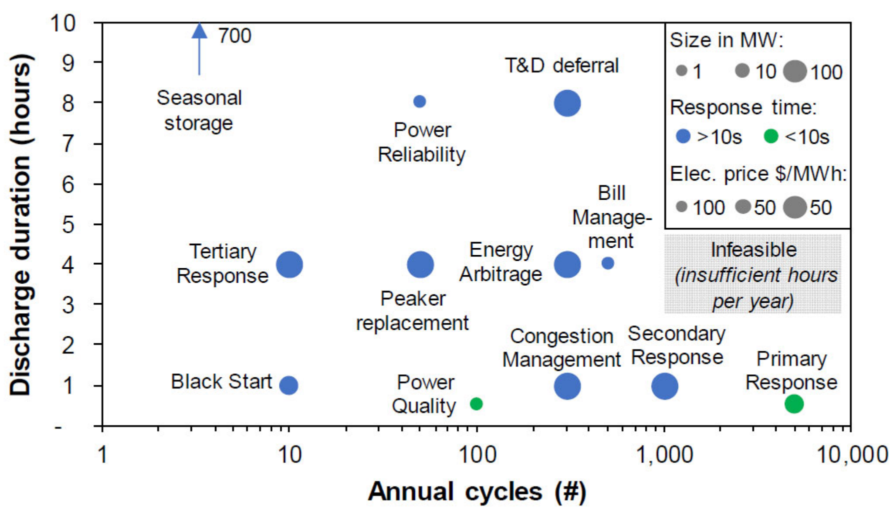
Deliverable energy densities assume efficiencies of 60% for hydrogen (fuel cells) and 40% for hydrocarbon fuels (IC Engine).

Part II – Grid Storage Cost

Storage Cost and Value

- The recurring question of value is one facing users and developers of storage.
  - Value determined by cost, system characteristics, use cases, and other available options (curtailment, demand response, trade, …)
  - The unicorn of strorage = "value stacking"
    - What services, "use cases". Try to combine/deliver multiple value streams
  - Total system cost change for delivery of service
    - Is marginal cost of storage less than savings by addition of intermittent supply?
- Storage cost
  - Per unit power, per unit energy?…
- What about losses and finite discharge/charge rates?
  - Can we predict when it will be needed to dispatch storage effectively?

Grid Storage Services and Characteristics



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Cost reductions due to learning

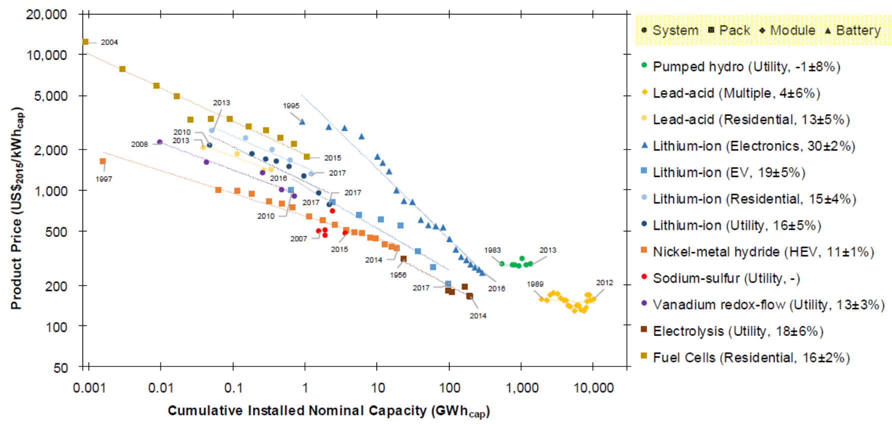

***Figure S2** – Updated experience curve data set based on Schmidt, 2017[28]. All lithium-ion and redox-flow data sets have been updated to include 2016 and/or 2017 data. The data set including future price projections can be downloaded[29].*

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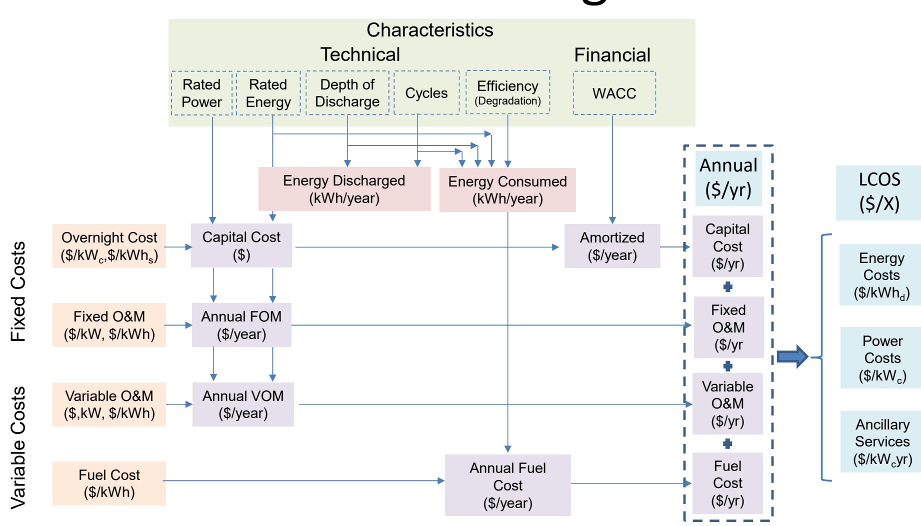
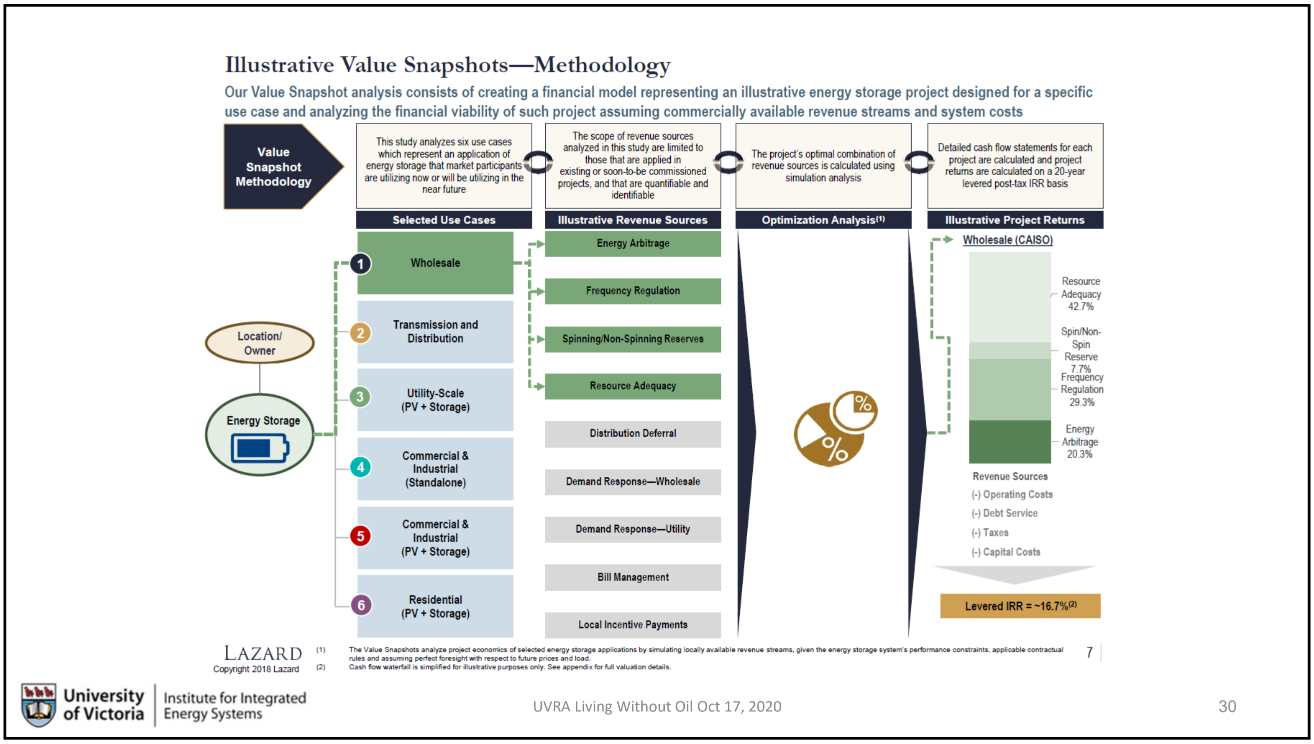
Annual Cost of Storage → LCOS




Illustrative Value Snapshots—Methodology
Our Value Snapshot analysis consists of creating a financial model representing an illustrative energy storage project designed for a specific use case and analyzing the financial viability of such project assuming commercially available revenue streams and system costs
Value Snapshot Methodology
This study analyzes six use cases which represent an application of energy storage that market participants are utilizing now or will be utilizing in the near future
The scope of revenue sources analyzed in this study are limited to those that are applied in existing or soon-to-be commissioned projects, and that are quantifiable and identifiable
The project's optimal combination of revenue sources is calculated using simulation analysis
Detailed cash flow statements for each project are calculated and project returns are calculated on a 20-year levered post-tax IRR basis
Selected Use Cases
Illustrative Revenue Sources
Optimization Analysis(1)
Illustrative Project Returns
Location/ Owner
Energy Storage
1 Wholesale
2 Transmission and Distribution
3 Utility-Scale (PV + Storage)
4 Commercial & Industrial (Standalone)
5 Commercial & Industrial (PV + Storage)
6 Residential (PV + Storage)
Energy Arbitrage
Frequency Regulation
Spinning/Non-Spinning Reserves
Resource Adequacy
Distribution Deferral
Demand Response—Wholesale
Demand Response—Utility
Bill Management
Local Incentive Payments
Wholesale (CAISO)
Resource Adequacy 42.7%
Spin/Non-Spin Reserve 7.7%
Frequency Regulation 29.3%
Energy Arbitrage 20.3%
Revenue Sources
(-) Operating Costs
(-) Debt Service
(-) Taxes
(-) Capital Costs
Levered IRR = ~16.7%(2)
LAZARD
Copyright 2018 Lazard
(1) The Value Snapshots analyze project economics of selected energy storage applications by simulating locally available revenue streams, given the energy storage system's performance constraints, applicable contractual rules and assuming perfect foresight with respect to future prices and load.
(2) Cash flow waterfall is simplified for illustrative purposes only. See appendix for full valuation details.
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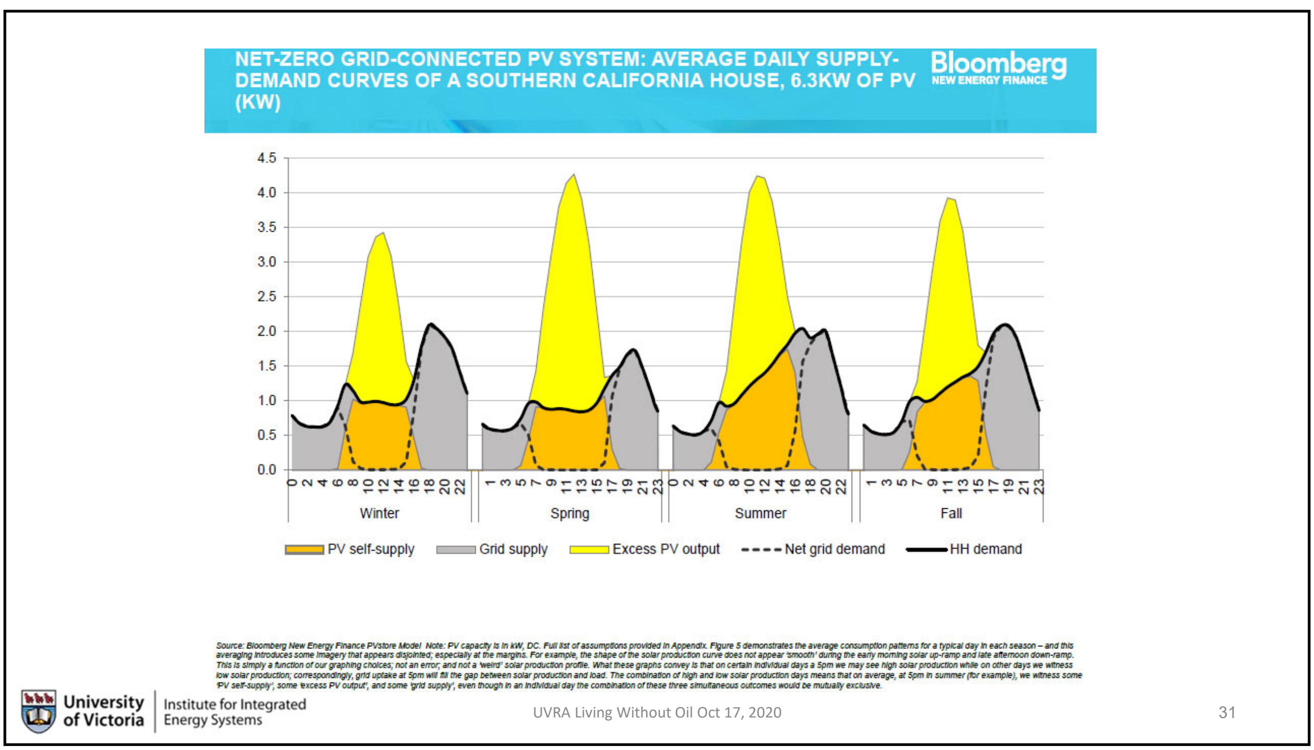
NET-ZERO GRID-CONNECTED PV SYSTEM: AVERAGE DAILY SUPPLY-DEMAND CURVES OF A SOUTHERN CALIFORNIA HOUSE, 6.3KW OF PV (KW)
Bloomberg
NEW ENERGY FINANCE
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Winter
Spring
Summer
Fall
PV self-supply
Grid supply
Excess PV output
Net grid demand
HH demand
Source: Bloomberg New Energy Finance PVstore Model Note: PV capacity is in kW, DC. Full list of assumptions provided in Appendix. Figure 5 demonstrates the average consumption patterns for a typical day in each season – and this averaging introduces some imagery that appears disjointed; especially at the margins. For example, the shape of the solar production curve does not appear 'smooth' during the early morning solar up-ramp and late afternoon down-ramp. This is simply a function of our graphing choices; not an error; and not a 'weird' solar production profile. What these graphs convey is that on certain individual days a 5pm we may see high solar production while on other days we witness low solar production; correspondingly, grid uptake at 5pm will fill the gap between solar production and load. The combination of high and low solar production days means that on average, at 5pm in summer (for example), we witness some 'PV self-supply', some 'excess PV output', and some 'grid supply', even though in an individual day the combination of these three simultaneous outcomes would be mutually exclusive.
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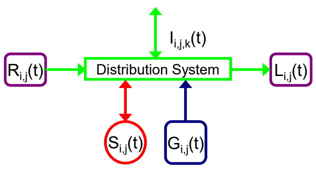
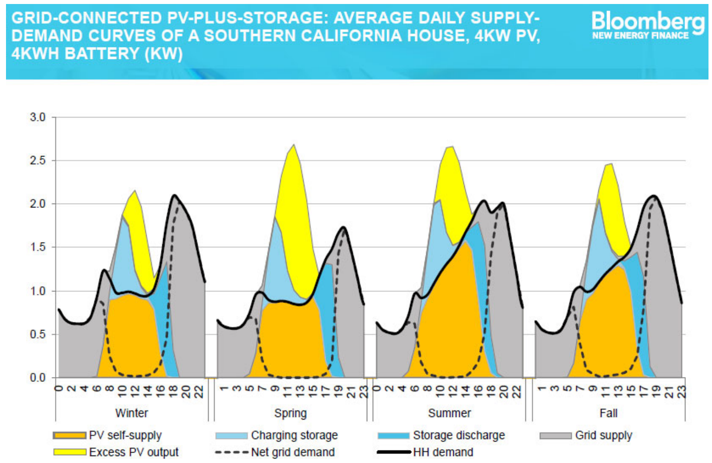
Storage

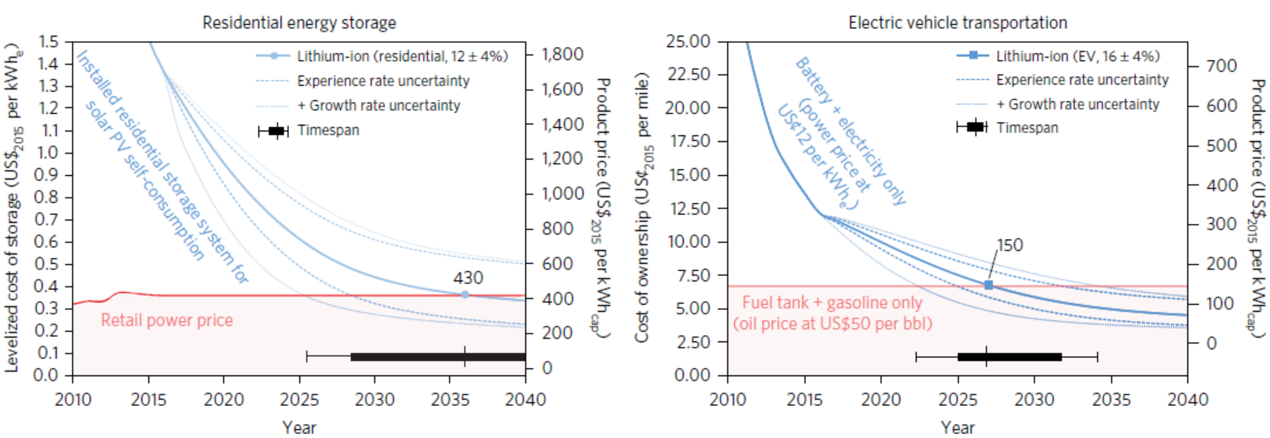


R – Renewable power supplies
L – Loads/Demands
S – Storage systems
G – Dispatchable generators
I – Interconnections



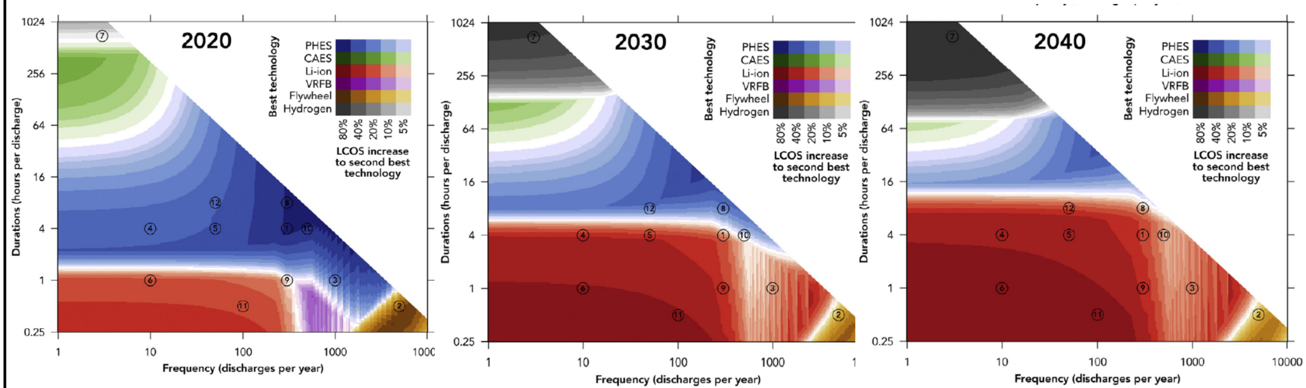
ource: Bloomberg New Energy Finance PVstore Model Note: PV capacity is in kW, DC; storage capacity is in kWh, nameplate. Full list of assumptions provided in Appendix.

Experience Curve Effects



Schmidt 2017 The Future costs Levelized Cost of Electrical energy storage based on experience rates, Nature Energy, 2, 2017

Storage LCOS Ranking



Schmidt 2019 Projecting the Future Levelized Cost of Electricity Storage Technologies, Joule, 3, 81-100, Jan 2019

Summary

- Flexibility requirements increasing due to a number of different supply and demand factors
- In principle, storage provides a range of services
- Can be located near supply or demand
- Availability (storage dispatch), degradation, round-trip efficiency may reduce to value relative to other flexibility options
- Cost of storage (investment) and cost of storage not the same, but difficult to tell them apart

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