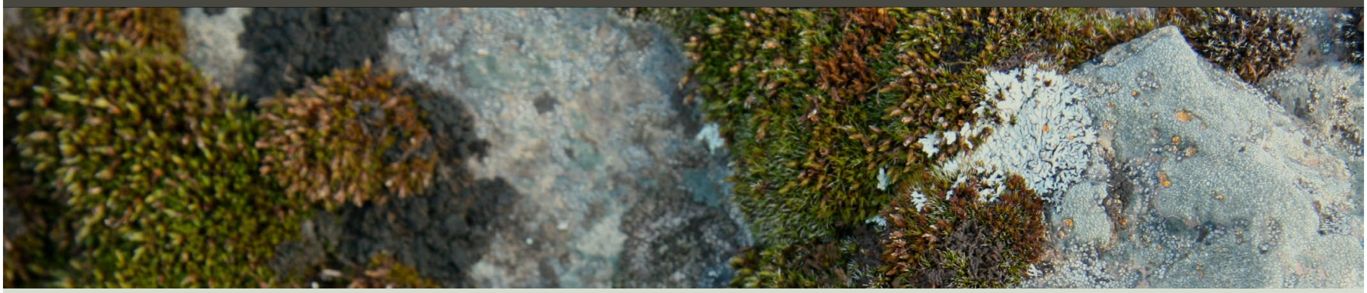
LV-2016-113

Landsvirkjun



Orkugeymsla

Samantekt

Lykilsíða

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Samvinnuaðilar:

Útdráttur: Skýrslan er afrakstur rannsóknarverkefnis sem unnið var sumarið 2016 á umhverfisdeild þróunarsviðs Landsvirkjunar. Í skýrslunni er yfirlit um leiðir til að geyma rafmagn með áherslu á stöðu tækni, væntingar um þróun og kostnað. Í henni er lýst helstu orkugeymsluaðferðum sem notaðar eru í orkugeiranum ásamt aðferðum sem nú eru í þróun. Margar orkugeymsluaðferðir sem fjallað er um í skýrslunni eiga ekki við fyrir íslenska raforkukerfið miðað við stöðu þess í dag. Vatn í miðlunarlónum vatnsorkuvera geymir mikla stöðuorku sem er miðlað eftir breytilegri orkuþörf. Miðlunarlónin henta líka vel til að miðla rafmagni þegar orkuvinnslan er háð veðri. Lönd sem nýta sólarorku og vind til raforkuvinnslu í umtalsverðum mæli og geta ekki reitt sig á miðlað vatnsafl eru háð orkugeymslu á stórum skala og þurfa því að auka geymslugetuna með stækkandi hlut vind- og sólarorku í orkukerfum sínum.

Lykilorð: Endurnýjanlegir orkugjafar, orkugeymsla, rafhlöður, dæluvirkjanir, loftþjöppunarstöðvar, hverfilhjól, þéttar

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Samþykki verkefnisstjóra Landsvirkjunar

Jón Ingimarsson

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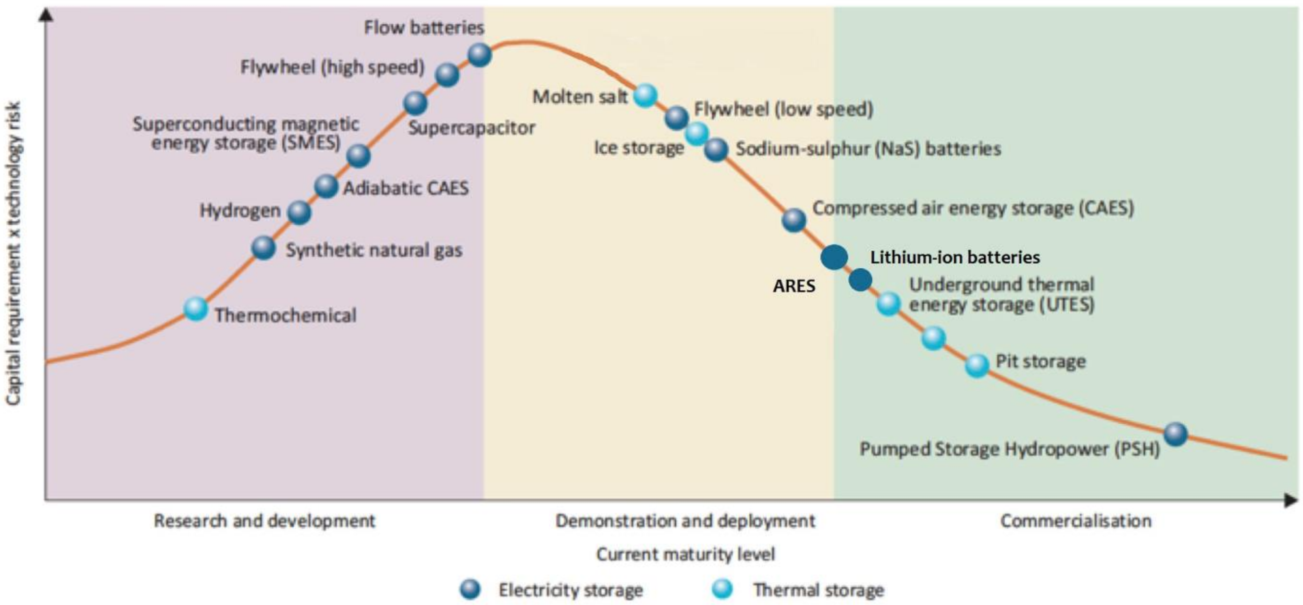
1 Inngangur

Þetta rannsóknarverkefni snerist um að taka saman upplýsingar um leiðir til að geyma rafmagn með áherslu á stöðu og væntingar um þróun orkugeymsluaðferða og einnig kostnað. Farið var yfir helstu orkugeymsluaðferðir notaðar í orkugeiranum ásamt þeim aðferðum sem eru í þróun. Margar orkugeymsluaðferðir sem fjallað er um í skýrslunni eiga ekki við í íslenska orkukerfinu. Vatn í miðlunarlónum vatnsorkuvera geymir mikla stöðuorku sem hægt er að miðla eftir breytilegri orkuþörf. Miðlunarlónin henta líka vel til að miðla rafmagni þegar orkuvinnslan er háð veðri. Því fer nýting vatnsorku og vinds vel saman. Lönd sem ekki geta reitt sig á miðlað vatnsafl eru háðari orkugeymslu á stórum skala og þurfa því að auka geymslugetuna með stækkandi hlut vind- og sólarorku í orkukerfum sínum.

Gríðarlega miklar framfarir hafa átt sér stað í orkugeymslu á undanförnum árum

Á svæðum þar sem vatnsafl er ekki til staðar er þörf á orkugeymslu með miðlum eins og rafhlöðum, hverfihjólum og ofur-rýmdarþéttum. Orkugeymslu þarf til að tryggja rekstraröryggi raforkukerfisins og afhendingu rafmagns til notenda sem þurfa mikið afhendingaröryggi eins og sjúkrahús og gagnaver. Í farartækjum má nýta hemlunarorku, o.s.frv.

Í þessari samantekt er stuttlega farið yfir rafhlöður, dæluvirkjanir, þrýstiloftsorkugeymslu (CAES), hverfihjól, orkugeymslu þungra byrða og ofurrýmdarþétta. Sjónarhorn höfundar er alþjóðlegt og hann einblínir ekki á neitt eitt land eða einn orkumarkað. Þó vísar hann til Íslands þegar við á.



Mynd 1: Þróun aðferða við orkugeymslu sem fjallað er um í skýrslunni [1].

2 Rafhlöður

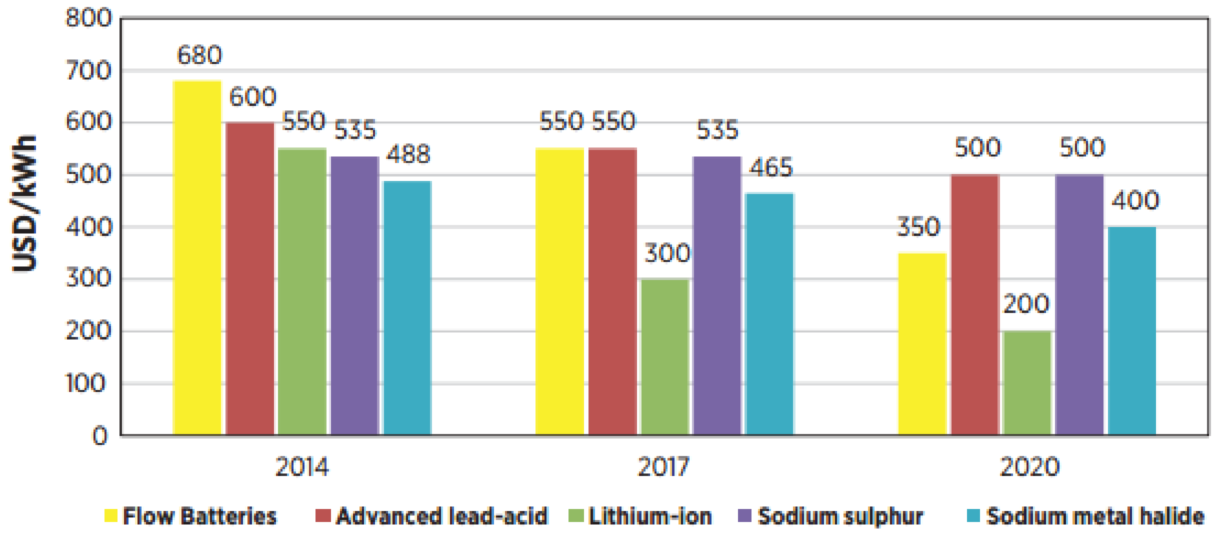
Miklar framfarir hafa orðið í þróun rafhlaðna undanfarin ár, sérstaklega hvað varðar litíum-ion og blýrafhlöður þar sem bylting hefur átt sér stað í þróun þeirra beggja. Rafhlöður geta uppfyllt skilyrði varaaflgjafa, þannig að keyrsla dísilrafala verður óþörf. Til að vera samkeppnishæfar þurfa rafhlöður að vera ódýrar, endast í a.m.k. tíu ár, hafa háa nýtni og geta hlaðið sig oft á dag án þess að það hafi áhrif á afköst þeirra.

Verð á rafhlöðum hefur lækkað, aðallega vegna niðurgreiðslna í innleiðingarfasa, stærðarhagkvæmni og fjöldaframleiðslu við þróun rafbíla. Til dæmis hófst bygging Tesla Gigafactory árið 2014 og reiknað er með að framleiðsla hefjist 2017. Áætlað er að þessi verksmiðja muni framleiða árlega fleiri litíum-ion rafhlöður en voru framleiddar á heimsvísu árið 2013. Tesla stefnir að því að lækka kostnaðinn per kílóvatt um 30%.

Mynd 2 sýnir áætlaðan kostnað fyrir fimm mismunandi tegundir rafhlaða. Þó að flæðirafhlöður, blýrafhlöður og natríum halógen rafhlöður eigi eftir að lækka í verði er talið að litíum-ion lækka mest. Natríum brennisteinsrafhöður er tækni sem mikil reynsla er komin á og því er ekki áætlað að kostnaðurinn við gerð þeirra muni lækka mikið.

Lækkun á verði rafhlaðna er m.a. vegna:

- Niðurgreiðslna
- Stærðarhagkvæmni
- Þróun og fjölgun rafbíla



Mynd 2: Áætlaður kostnaður rafhlaða árin 2017 og 2020 [3].

Samantekt um rafhlöðutegundir ræddar í skýrslunni má sjá hér að neðan.

Litíum-ion rafhlöður sem eru notaðar við tíðnistýringu á netinu hafa lækkað mest í verði. Endingin hefur lengst og stærðin hefur minnkað töluvert. Litíum-ion rafhlöður eru aðallega þekktar úr rafeindatækni og rafbílum, en þær geta sinnt kerfisþjónustu. Bæta þarf rafhlöðurnar á tvo vegu svo þær verði samkeppnisfærar: afkastatíminn þarf að verða lengri og endingin þarf að vera meiri en tíu ár þrátt fyrir fulla daglega afhleðslu.

Flæðirafhlöður einkennast af því að hafa langan afkastatíma fyrir lágt verð. Raflausnin er á vökvaformi og henni er dælt frá tönkunum til rafskautanna. Orkuafköst eru háð rúmmáli tankanna sem geyma raflausnina, og er auðvelt að auka þau með því að bæta við fleiri tönkum. Aflafköst eru háð stærð rafefnakersins. Þessi aðskilnaður orku- og afl-afkasta eykur sveigjanleikann í hönnun þessara rafhlaðna og gerir það kleift að stilla orku- og aflafköst fyrir viðeigandi álag. Annar kostur við flæðirafhlöður er að yfirhleðsla eða full afhleðsla (tæming) hefur ekki áhrif á afköst og þ.a.l. er endingin betri. Vanadium redox er mest rannsakaða flæðirafhlaðan og styttist í markaðssetningu hennar. UniEnergy Technologies (UET) hefur fengið mikla fjármögnun og fullyrðir fyrirtækið að flæðirafhlöður þess muni kosta milli USD 700 og 800 á kWst. og í framtíðinni jafnvel USD 500 á kWst. Aðal hindranirnar við markaðssetingu flæðirafhlaðna eru ending, en einnig hafa dælur og leiðslur átt það til að leka. Bein afleiðing af þessu er aukinn kostnaður sem kemur í veg fyrir samkeppnishæfni rafhlaðnanna og eru þær því ekki samkeppishæfar.

Blýrafhlöður eru oft notaðar í orkufreka þætti, t.d. tíðnistýringu og varaafl. Ókostir þeirra eru stutt ending, hæg hleðsla og mikið viðhald. Fyrirtækið Ecoult hefur þó mark- aðssett rafhlöðu sem kallast Ultrabattery, sem er nýtt í rafbílum og álagsdreifingu.

Álrafhlöður eru ný tækni sem ennþá er verið að þróa. Árið 2015 þróuðu rannsóknar-teymi við Stanford háskóla prótótýpu og héldu því fram að þessi rafhlaða hefði ýmis forskot yfir litíum ion rafhlöður. Rannsóknarteymið heldur því fram að rafhlaðan þeirra geti hlaðið sig á einni mínútu, en orkurýmd hennar var ekki birt. Einnig var sagt að hún gæti endurhlaðið sig 7.500 sinnum án þess að afköst minnkuðu, miðað við einungis 1.000 hleðslur í litíum-ion rafhlöðum. Nokkrir gallar eru við þessa tækni. Til dæmis hefur Scientific American bent á að orkuþéttleiki álrafhlöðunnar sé einungis einn fjórði þétt- leika jafn stórrar litíum-ion rafhlöðu. Því þyrftu álrafhlöður að vera fjórum sinnum þyngri til ná sömu afköstum, og því er ólíklegt að þessi rafhlaða verði notuð í rafeindatækni eða rafbíla á næstunni.

Rafhlaða úr fljótandi málmum Helstu vandamál rafhlaða á föstu formi eru minnkandi afköst með tímanum og mekanísk niðurbrot. Til að koma í veg fyrir þessi vandamál hafa verið gerðar merkilegar rannsóknir við MIT háskóla með rafhlöður á fljótandi formi. Kostir slíkra rafhlaða er lágur framleiðslu- og hráefniskostnaður, löng ending og áreiðanleiki. Þar sem rafskautið er á vökvaformi geta ekki myndast sprungur og því eiga þessar rafhlöður ekki við mekanísk niðurbrot að stríða, sem bætir endinguna. Þessar rafhlöður eru hannaðar fyrir risageymslu (e. bulk storage) og eiga að geta geymt umframorku frá vindlundum og sólarorkuverum meðan eftirspurn er lítil, og síðan skilað orkunni þegar álag á kerfið er mikið eða þegar þessi orkuver skila minni orku inná kerfið. Þar að auki geta þessar rafhlöður gegnt mikilvægu hlutverki í kerfisþjónustu.

Þróun þessarar tækni hefur aðallega falist í því að finna hráefni sem eru ódýr, endingargóð og fáanleg í miklu magni til að gera framleiðsluferlið sem hagkvæmast. Rannsóknarfólkið við MIT byrjaði á því að nota magnesíum sem efra rafskautið og antimóný sem það neðra. Síðan áttaði það sig á því að hægt væri að bæta við blýi til að lækka rekstrarhitastigið. Þróunin í þessum rafhlöðum gekk vel og stofnað var fyrirtækið Ambri árið 2010 til að halda áfram með þróunina. Áætluð markaðssetning var 2016, en vandamál með lok á rafhlöðunni hefur valdið töfum. Þrátt fyrir þetta halda margir að þessi tækni eigi eftir að valda byltingu í orkugeymsluaðferðum. Kostnaðurinn á kWst. er áætlaður USD 500. En þar sem gert er ráð fyrir að litíum - ion rafhlöður kosti USD 200 á kWst. og flæðirafhlöður USD 350 á kWst. árið 2020, er nauðsynlegt að kostnaðurinn lækki til að tæknin sé samkeppnishæf.

3 Dæluvirkjanir

Níutíu og sjö prósent raforku sem geymd er á heimsvísu til skemmri tíma er í miðlunarlónum dæluvirkjana. Þetta er hagkvæmasta leiðin til að geyma rafmagn til skamms tíma eins og staðan er í dag, en þróun annars konar tækni hröð. Kostir þessarar tækni er hvað hún bregst fljótt við þegar snögg breyting verður á álagi kerfisins og sá að þessi tækni bakkar upp endurnýjanlega orkugjafa eins og vind og sól sem nýttir eru til raforkuvinnslu. Helstu ókostir við dæluvirkjanir eru erfiðleikar við að finna stað til að reisa slíka stöð og tíminn sem tekur að byggja þær.

Þróun dæluvirkjana hefur aðallega verið í snúningshraðastýringu rafala. Það hefur aukið sveigjanleika í raforkukerfinu þegar vindlundir og sólarorkuver eru tengd við það. Önnur þróun er að nota sjóinn sem neðra miðlunarlón sem gerir auðveldara að finna slíkum virkjunum stað. Það er einungis ein slík stöð í rekstri í dag og hún er í Okinawa í Japan.

4 CAES

Þessi aðferð geymir orku sem stöðuorku í þjöppuðu lofti. Svipað og dæluvirkjun, þá notar þessi tækni ódýrt rafmagn þegar eftirspurn er lítil og losar sig við orkuna þegar eftirspurn er mikil. Þar af leiðandi gegnir þessi tækni líka mikilvægu hlutverki í samrekstri við vind og sólarorku. Þessar stöðvar koma í veg fyrir að það þurfi varaafl frá dísilrafstöðvum vegna þess að þær hafa mikil jöfunarorkuafköst og getu sem varaaflstöðvar í stuttan tíma.

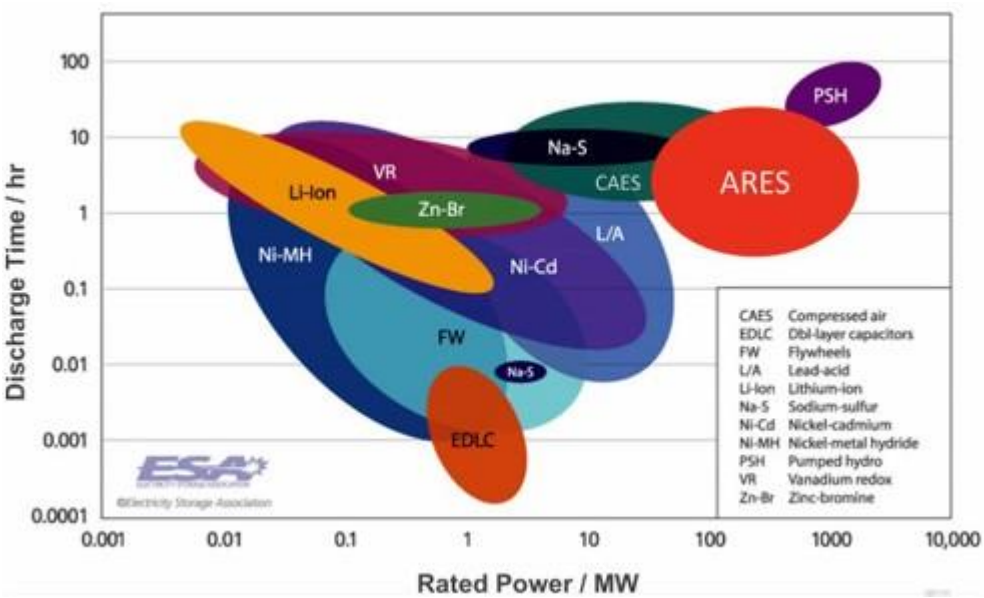
Það eru einungis tvær loftþjöppunarstöðvar í rekstri í heiminum, ein í Huntorf, Þýskalandi og hin í Alabama í BNA. Báðar stöðvarnar byggja á díabatísku aðferðinni og nota jarðgas til að hita loftið þegar það fer í hverfilinn. Fyrirtækið RWE er að þróa adíabatíska loftþjöppunar- stöð sem kallast ADELE. Þessi aðferð notar ekki jarðgas, en endurnýtir í staðinn hitann sem losnar við þjöppunina til að hita loftið áður en það fer í hverfilinn. Lightsail Energy er einnig að þróa adíabatíska loftþjöppunarstöð sem notar vatnsúða til að geyma varmann sem myndast við þjöppun og nota hann síðan þegar loftið fer í hverfilinn. Fyrirtækið stefnir að því að geta keppt við dísilstöðvar. Ókosturinn við þessa aðferð er sá að stóran helli þarf til að geyma loftið.

5 Hverfilhjól

Hér er orka geymd í hreyfingu þyrils. Helstu kostir hverfihjóla umfram rafhlöður er lítil mengun við framleiðslu og rekstur, ásamt þoli fyrir hita. Nútíma hverfihjól eru með segullegu og lofttæmt rými sem lágmarkar orkutap. Hverfihjól nota mótorrafal sem notar rafmagn þegar raforkuverð er lágt til að koma þyrlinum, sem knýr rafalinn, af stað. Endingartími hverfihjóla skiptir áratugum og þau þarfnast mjög sjaldan viðgerða. Það sem einkennir hverfihjól er að viðbragðstíminn er mjög stuttur og þau geta farið frá algerri afhleðslu í fulla hleðslu á nokkrum sekúndum. Hverfihjól eru sérstaklega nothæf í varaaflgjöfum. NASA hefur unnið með Power Tree Corp. til að markaðssetja G6 svinghjólið sitt, sem verður notað í tíðnistýringu, spennustýringu og stjórnun á eftirspurn. Beacon Power byggði 20 MW orkugeymslustöð þar sem 200 hverfihjól voru tengd og taka þátt í tíðnistýringu á netinu í New York.

6 Stöðuaflsstöð

Fyrirtækið ARES er nýbúið að fá samþykkt að reisa 50 MW / 12.5 MWh orkugeymslukerfi. Kerfið notar ódýrt rafmagn á meðan eftirspurn er lág til að keyra þunga lestarvagna upp brekku. Þegar eftirspurn á orku er há, þá eru vagnarnir sendir niður brekku, sem knýr rafala. Þessi orkugeymslustöð verður á yfir 43 hektara landsvæði í Nevada og áætlaður kostnaður er 55 milljónir dollar. Bygging hennar á að hefjast seint á árinu 2017 eða snemma árs 2018 og áætlað er að rekstur hefjist 2019. Stöðin á að taka þátt í tíðni- og spennustýringu og þ.a.l. auðvelda tengingu endurnýjanlega orkugjafa eins og vinds og sólarorku við netið. ARES fullyrðir aða tækni sín kosti minna á öllu vistferlinu (levelized cost of energy – LCOE), hafi hærra hlutfall orku á móti afli en hvefihjól og betri nýtni en dæluvirkjun. Mynd 3 sýnir samanburð á ýmsum orkugeymsluaðferðum sem fjallað hefur verið um. Eins og sést, þá getur ARES afkastað hundruð MW af afli í nokkrar klukkustundir.



Mynd 3: Aflgeta á móti orkugetu ýmissa orkugeymsluaðferða [3].

7 Ofurrýmdarþéttar

Þó að rafhlöður hafi tiltölulega háa orkugetu, þá er hleðslutími þeirra mjög langur. Venjulegir þéttar hlaða sig hins vegar á örskammri stund en hafa takmarkaða orkugetu. Aftur á móti hafa ofurrýmdarþéttar háa aflgetu og töluvert hærri orkugetu en venjulegir þéttar. Þess vegna eru ofurrýmdarþéttar notaðir þegar þörf er á mikilli orku sem er ítrekað geymd og flutt í skömmtum. Tæknin á sér því notagildi í varaafli og álagsdreifingu á orkunetinu. Bæði hverfihjól og offurrýmdarþéttar eru til dæmis sérstaklega vel til þess fallin að brúa skammtímastraumleysi (nokkrar sekúndur upp í nokkar mínútur). Á undanförnum árum hafa ofurrýmdarþéttar verið notaðir í stór-skala varaaflgjafa (e. uninterupted power supply - UPS) þar sem þeir geta aukið áreiðanleika, lengt uppitíma og lækkað rekstrarkostnað. Nánar er farið í notagildi ofurrýmdar- þétta og svinghjóla í ramma 1.

RAMMI1: NOTAGILDI OFURRÝMDARÞÉTTAOGSVINGHJÓLA

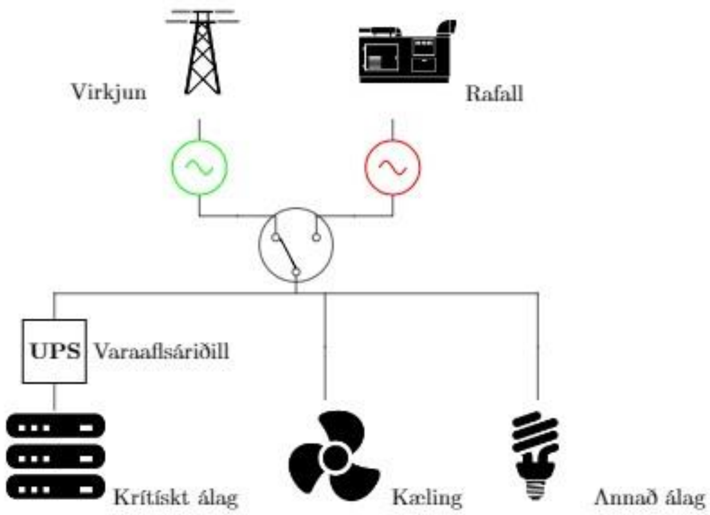
Stoðveitukerfi: Stoðveitukerfi Landsvirkjunar eru afar mikilvægt fyrir rekstraröryggi raforkukerfisins ásamt því að halda fjarskiptakerfum sem stýra og verja bæði aflstöðvar og flutningskerfi raforku gangandi. Þegar verið er að skipta frá virkjun yfir í varaaflsstöð, þá eru oftast notaðar blýrafhlöður til að brúa bilið á meðan rafallinn er ræstur. Ofurrýmdarþéttar gætu verið betri kostur en rafhlöður því þeir bregðast hraðar við, krefjast minna viðhalds, endasttöluvertlengurogmengatil- tölulega lítið viðförgun.Aðalókosturinnvið þessa þétta er lægriorkurýmd,enrafalareru yfirleitt einungis nokkrar sekúndur eða mínútur að komast sér í gang.

Gagnaver: Í gagnaverum sem geyma mikilvæg gögn er þörf á orkugeymslu til að koma í veg fyrir tap á gögnum eða eyðileggingu netþjóna vegna ofhitnunar við truflanir í raforkukerfinu. Víða eru notuð stór, hefðbundin rafgeymasett sem yfirleitt samanstanda af blýrafhlöðum og þurfa reglulegt viðhald og álagsprófanir. Þar sem truflanir eru tíðar minnka rýmdareiginleikarnir, sem styttir líftíma rafhlöðunnar. Nýjar lausnir eru varaaflgjafar sem samanstanda af annað hvort ofurrýmdarþéttum, svinghjólum eða litlum rafhlöðum og eru notaðir til að brúa skammtímastraumleysi á meðan annar varaaflgjafi er ræstur og tekur við álaginu. Þessir aflgjafar eru oft einungis nokkrar sekúndur eða mínútur að fara í gang og því þarf ekki mikla orkugeymslu. Þessir orkugeymslumiðlar hafa ýmis forskot yfir hefðbundnar stoðveitur sem reiða sig á stór rafgeymasett. Ofurrýmdarþéttar geta til dæmis aukið rekstraröryggi, minnkað kostnað og einfaldað viðhaldsferla. Ofurrýmdarþéttar hafa þann kost að hægt er að hlaða og afhlaða þá nánast endalaust án þess að minnka afköst. Samanburð þriggja orkugeymsluaðferða má sjá í töflu 4 hér að neðan. Mynd 5 sýnir flæði rafmagns í gagnaveri.

Endurnýting hemlunarorku: Endurnýta má hemlunarorka ökutækja með notkun ofurrýmdarþétta. Samkvæmt Paumanok Publications Inc., eru ofurrýmdarþéttar sem notaðir eru í almenningssamgöngur fjörutíu prósent af ofurrýmdarþéttamarkaðinum. Rannsóknir sýna að með því að endurnýta helmlunarorka væri hægt að minnka orkunotkun um 10 til 45% í farartækjum .

	Rafhlöður	Ofurrýmdarþéttar	Svinghjól
Typical runtime	5 minutes to 8 hours	10 seconds to 1 minute	1 second to 1 minute
History in the marketplace	Long (many decades)	Short (a few years)	Longer for low speed, short for high speed
Operating conditions	Narrow temperature range	Wide temperature range	Wide temperature range
Environmental impact	Harmful (lead) if not recycled, hydrogen release on recharge	Harmful if burned	Harmful (circuit boards) if not recycled
Safety	Significant government and local regulations for management of lead and acid	Requires high voltages to operate	Encasements may be required for higher rpm flywheels (in case of breakage while spinning)
Power range	Up to multiple megawatts	Up to tens of thousands of kilowatts	Up to multiple megawatts
Reliability	Moderate (higher for shorter runtimes)	High	Moderate (higher for newer technologies)
Maintenance	Moderate for VRLA Higher for vented / flooded	Moderate	Moderate for carbon fiber Higher for older technology
Recharge time	10 x discharge time	Seconds	Seconds or minutes
Number of deep charge/ discharge cycles	Up to 3,000	Up to 1 Million	Unlimited (assuming maintenance)

Mynd 4: Samanburður eiginleika þriggja orkugeymsluaðferða sem notaðir eru í gagnaverum [2].



Mynd 5: Flæði rafmagns í gagnaveri [2].

8 Lokaorð

Orkugeymsla gegnir margvíslegu hlutverki og engin ein aðferð hentar í öllum tilfellum. Stækkandi hlutdeild endurnýjanlegra orkugjafa eins og vinds og sólarorku í raforkuvinnslunni kallar á aukna orkugeymslum sem í senn er hagkvæm og hægt að grípa til með öruggum hætti og fyrirvaralítið. Ljóst er að tækniframfarirnar eru gífurlega hraðar og það verður spennandi að fylgjast með því hvað framtíðin ber í skauti sér.

9 Heimildir

[1] IEA: Roadmap targets. (2014). Sótt þann 22. júlí af https://www.iea.org/media/freepublications/technologyroadmaps/foldout/FOLDOUT_TechnologyRoadmapEnergystorage_2014.pdf

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10 Viðauki: Orkugeymsla

UMHVERFISDEILD ÞRÓUNARSVIÐS

Orkugeymsla

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August 19, 2016

Abstract

This research paper investigates methods of storing electricity for grid-scale applications. The focus is on the development and cost of current energy storage methods, as well as those that have shown promising results and will see commercialization in the near future. The constant challenge of balancing supply with demand has been complicated by the emergence of intermittent renewable energy sources, such as wind and solar. Accordingly, a market for energy storage technologies to serve on the grid has arisen. Energy storage is used to counteract the intermittency; to avoid the curtailment of excess energy when supply exceeds demand and to release stored energy during peak load times. Many of the technologies discussed in this paper make use of load-leveling, that is, they store energy during periods of low demand and deliver it during periods of high demand, for a higher price. They are capable of providing multiple ancillary services, making them more flexible grid resources than traditional, fossil-fuel dependent generators, without leaving a carbon footprint. Various forms of energy storage, including electrochemical, hydro, thermal, kinetic, gravitational and electrostatic, are explored in this paper and a comprehensive assessment of their cost, contribution to the grid, and development is presented. The report gives an overview of the status of energy storage in the world today without necessarily focusing on one country or region.

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Acronyms

ACAES adiabatic compressed air energy storage

ADELE Der Adiabate Druckluftspeicher fur die Elektrizitatsversorgung

ARES Advanced Rail Energy Storage

CAES compressed air energy storage

CES cryogenic energy storage

EV's electric vehicles

FCEV's fuel cell electric vehicles

FESS Flywheel energy storage systems

HES Hydrogen energy storage

HLES Heavy load energy storage

LAES Liquid air energy storage

LMB's liquid metal batteries

MHE material handling equipment

PEV plug-in electric vehicle

PHES pumped-heat electrical storage

RES renewable energy sources

SEPTA Southeast Pennsylvania Transit Authority

SMES superconducting magnetic energy storage

UPS uninterrupted power supply

V2G vehicle-to-grid

VRLA valve-regulated lead acid

Chapter 1

Introduction

Grid energy storage

As the integration of intermittent renewable energy sources (RES) into the power grid increases, so does the need for energy storage. Making supply equal to demand is especially difficult with intermittent RES, since humans cannot control the wind or sun. Energy storage has the potential to not only allow for the transition to intermittent RES but making the power grid more resilient, reliable, and efficient. As a direct result, grid storage could help RES, such as wind and solar, to compete with traditional energy sources that rely on fossil fuels. The ability to store energy on the grid will be critical for emergency preparedness and ancillary services, such as frequency regulation [23]. The U.S. Department of Energy identifies four main challenges to the integration of energy storage to the grid: cost competitive energy storage technology, validated reliability and safety, equitable regulatory environment, and industry acceptance. Overcoming these challenges will allow for the large-scale deployment of energy storage technologies.

Batteries, pumped hydro, flywheels, compressed air energy storage, etc. are all examples of technologies used to store energy. When connected to the grid, these technologies can provide frequency and voltage regulation, load leveling, back-up power, grid stabilization, bulk storage, etc. (see appendix D), however, not every energy storage technology is suitable for each application. As a result, a portfolio strategy is essential for grid energy storage. An energy storage system has greater flexibility than traditional grid resources, such as diesel generators and turbines, because energy storage technologies are capable of providing multiple services to the grid [23].

A robust, reliable, and efficient grid will be vital for meeting increased power demand and decreased carbon emissions. Smart grids will play an instrumental role with energy storage on the grid, as well as the integration of intermittent RES. As will be discussed in Chapter 2, vehicle-to-grid technologies rely on smart grids to utilize the power from parked electric vehicles. Smart grids provide superior efficiency and bring many benefits to both the utilities and the consumer, including greater control over pricing and decreased dependence on fossil-fuel powered generators. The demand response capabilities of smart grids will allow for variable pricing of electricity and smart metering, where requests or fluctuations in price can be directly communicated to end-users [26]. To further increase the grid's efficiency, automation technology is incorporated in the smart grid to allow the utility to control any number of devices from a centralized location [27]. The clear financial and environmental benefits of smart grids will revolutionize electrical systems [25].

Chapter 2

Potential of PEV's to Provide Demand Response and Ancillary Services

The emergence of intermittent renewable energy sources (RES) into the existing power grid will require appropriate infrastructure for its integration. The variable output and unpredictability of RES, such as wind and solar technologies, pose a challenge to our ability to balance energy generation with demand. Energy storage is hence crucial in order to compensate for the variable output. The incoming market of electric vehicles (EV's) is a potential source to balance the grid, both as demand response resources and as ancillary service providers [5].

2.1 Demand response

Demand response is a tool that makes use of financial incentives to the end-user to shift and/or decrease their energy usage at peak times during the day [6]. This resource is becoming increasingly important to balance supply and demand with the integration of intermittent RES in the grid. EV's are flexible loads and can therefore be used to optimize grid operations. If connected to a smart grid, vehicle owners would have the ability to limit the amount of discharge from the battery to ensure that they would have enough range for their next drive [8]. It is essential that we modernize our grid technology to allow for optimal grid operation, and it is vital to invest in the sufficient infrastructure required for the integration of intermittent RES to the power grid.

2.2 Ancillary services

The concept behind vehicle-to-grid (V2G) energy distribution is that battery and fuel cell powered vehicles can supply power back to the grid. V2G could be an effective way of balancing loads on the grid when demand is high. Due to the fact that cars are parked on average 95% of the time, there is an opportunity to exploit the balancing power of EV's. They could act as buffers of power by storing excess energy, e.g. during windy periods, which can then be delivered back to the grid during peak load times. Vehicles could then be recharged at a lower cost during off-peak hours, thus, introducing a financial incentive for vehicle owners [7]. Owners of EV's would furthermore be compensated for the power delivered back to the grid, effectively lowering the life-cycle cost of owning an EV [12]. However, in order for EV's to be V2G capable, the battery must be bidirectional, meaning that it can both charge from the grid and discharge to the grid. The flow of power for three types of electric vehicles can be seen in figure 2.2. When implemented, a system operator would be able to dispatch renewable resources via vehicle batteries during high demand. By contrast, during periods of low demand, the batteries would store the excess energy [10]. The driver and/or

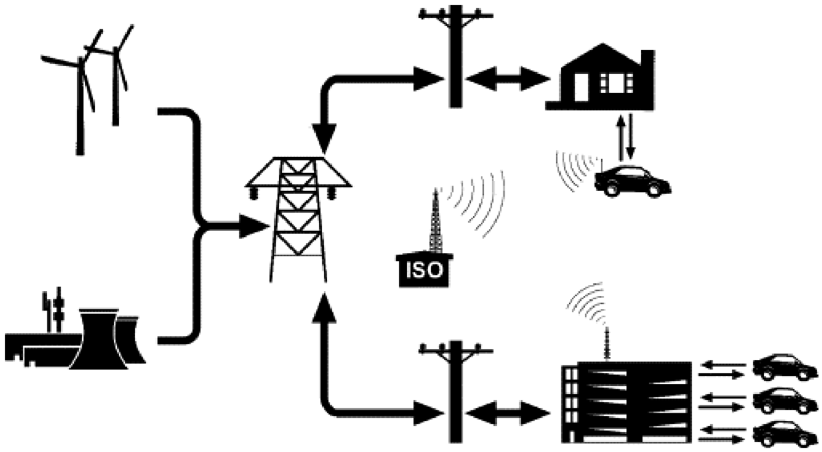


Figure 2.1: Vehicle-to-grid schematic diagram

system operator would limit the amount of discharge to ensure enough battery power for driving. The three requirements for cars to be V2G capable are:

- A power connection to the grid for electrical energy flow
- Control/logical connection for communication with grid operators
- Precision metering on-board the vehicle [11].

Diagram 2.1 illustrates the wireless control connections between EV's and the power grid. According to Chakraborty et al., the annual revenue estimate for 10 kW vehicle could provide between USD 920 and 1117 for spinning reserves and USD 2497-3285 for regulation. It should be noted, however, that based on today's battery technology, it is easier to design an EV battery with spinning reserve capabilities than one that provides regulation services [10].

Generators powered by fossil fuels have traditionally been used as ancillary service providers for many countries; however, they do not respond as quickly as advanced storage assets and require significant maintenance, which can be costly [2]. EV's, on the other hand, upon receiving a signal from the operator, could respond within milliseconds to change the power output. V2G has the potential to eliminate the need for rapidly ramping generators, decreasing both costs and emissions [15]. Of course this is not directly applicable to the Icelandic power grid where fossil-fueled generators are only used for backup power.

2.3 Cost structure

It is important to note that spinning reserves and regulation are paid by capacity, that is, by the total power available. V2G owners would be paid for the time of availability, regardless of whether any power is transferred from the vehicle to the grid or not. Power from fleets of cars would have to be aggregated from individual vehicles to reach minimum capacity requirements demanded by the market. This aggregated power would subsequently be sold to grid market participants [12].

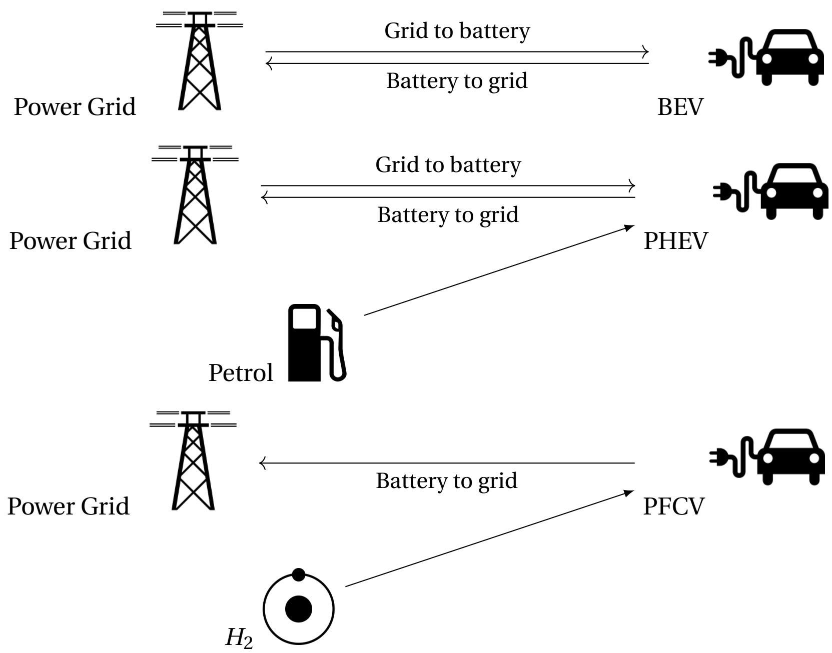
The relationship between V2G owners and aggregators could be contractual or non-contractual. For the former, owners would sign a contract that obligated them to have their car available to serve the grid for a certain number of hours each week or month. Contracts would be especially beneficial for the aggregator, giving him or her more certainty in the available power capacity. In the non-contractual structure, on the other hand, owners would be paid for the capacity that they provide with no obligations. One study shows, notably, that owners dislike signing V2G contracts. This is most likely due to the lack of flexibility in car use and their obliviousness to how long their car is parked. As a result, customers demand higher prices to sign contracts, making V2G power less competitive on the grid. Owners would most likely prefer a non-contractual pay-as-you-go structure or upfront cash payments in exchange for signing a contract. Both approaches would eliminate uncertainty with contracts and allow for V2G power to be more competitive on the grid [12].

2.4 Relevance to Iceland

At the end of 2015, only 1,4% of cars in Iceland were plug-in electric vehicles. In order to decrease greenhouse gas emissions by 40% (the Icelandic government's goal in accordance with the European Union's target [16]), a significant number of car owners must switch to PEV's. The Icelandic government has encouraged the sale of EV's by eliminating the excise and value-added tax on such vehicles [18, 17]. However, the limited range of EV's and the insufficient number of charging stations appear to be the largest deterrents to their mass-use. As far as V2G's relevance in Iceland, there is absolutely no need for the additional energy storage in Iceland's power grid. Hydro power significantly supports the base load and the addition of intermittent RES would simply reduce the reliance on hydro power at certain points in the day. Any intermittent source would simply be integrated with the hydro power, making it unnecessary to store energy in EV's.

Widespread adoption of electric vehicle technology will require massive installations of EV infrastructure, such as charging stations outside of apartment buildings, supermarkets, etc. For this to occur, government subsides would be imperative due to the costly nature of new infrastructure. In the case of charging stations in public parking lots, a pricing system for using parking lots and charging vehicles could be put in place. However, different types of EV's require different charging infrastructure. This complicates the installation of stations and is more costly.

Figure 2.2: Power flow diagram for three types of EV's [19].



ACRONYMS

BEV - Battery electric vehicle
PHEV - Plug-in hybrid electric vehicle
PFCV - Plug-in fuel cell vehicle

Chapter 3

Utility-Scale Battery Storage

Although over 97% of the world's large-scale energy capacity in 2014 was from pumped hydro storage, utility-scale battery technology has seen significant developments over the past decade. This is partially due to increased government subsides for battery research and development, as well as regulations to decrease dependence on fossil fuels. The large-scale battery market is expected to grow from USD 220 million of annual revenue in 2014 to 18 billion in 2023. As a result, power capacity is estimated to increase from 360 MW to 14 GW from 2014 to 2023 [41]. In 2014, sodium-sulfur was the leading utility-scale battery in terms of power capacity. The battery storage market, however, is transitioning from sodium-sulfur batteries to lithium-ion and advanced lead acid. The increased deployment of lithium-ion batteries is partially due to its superior performance in several categories along with decreasing costs. Compared to other batteries, lithium-ion batteries are often superior in energy and power density, cycle and calendar life, and cost [41].

Instead of using fossil-fuel dependent facilities, batteries can fulfill requirements for reserve generation, thus, drastically improving efficiency and lowering operating costs. Energy storage enables the integration of RES and improved power quality and robustness. The mass deployment of batteries on the grid must meet industry demands of low cost, lifetimes of at least ten years, high efficiency, and cycle durability [46].

3.1 Cost of batteries

The leading factors contributing to the decreased cost of batteries in recent years are economies of scale, manufacturing capacity, and the development of EV's. Additionally, greater demand for frequency regulation, in part due to the integration of intermittent RES's, has facilitated the deployment of large-scale batteries [41, 42]. The increased interest in EV's has already led to increased economies of scale; construction of the Tesla Gigafactory began in 2014 and it is expected to begin cell production in 2017. The Gigafactory will be the largest lithium-ion factory in the world, and by 2020, the factory is expected to produce more lithium-ion batteries than were produced worldwide in all of 2013. Tesla plans to use these economies of scale to reduce the cost per kilowatt of its battery by over 30% [43]. Figure 3.1 shows the estimated costs of energy per kilowatt in 2017 and 2020 for various types of batteries. Although advanced lead-acid batteries, flow batteries, and sodium metal halide batteries are projected to decrease in cost due to increased deployment, competition, and technology improvement, these reductions will be less drastic than for lithium-ion batteries. Sodium sulfur, a considerably mature battery chemistry, will see small reductions in cost, if any.

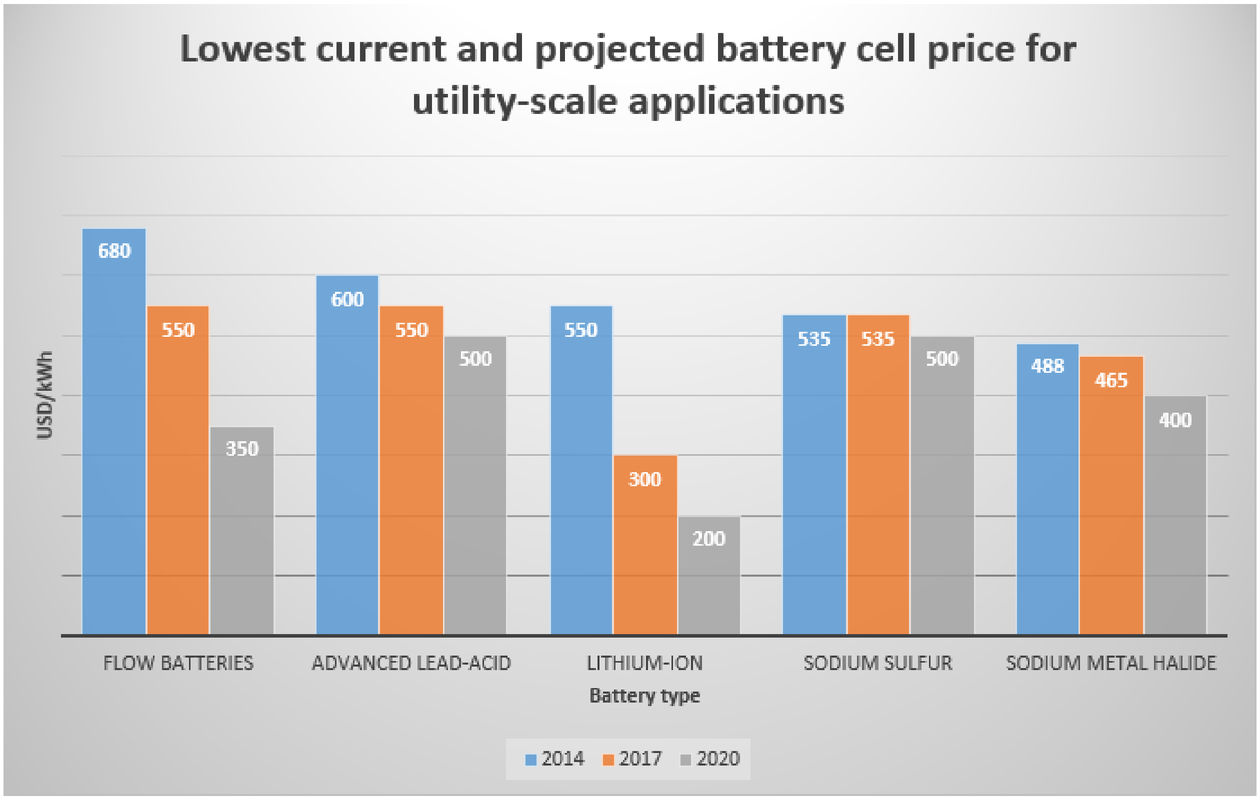


Figure 3.1: Price of energy per kilowatt hour for five common battery types [41].

3.2 Lithium-Ion batteries

Lithium-ion batteries for grid-scale storage for frequency regulation have seen the largest decrease in costs, from roughly USD 2400/kWh in 2008 to USD 600/kWh in 2013. During this same time period, the cycle life times increased by 150%, from 2000 to 5000 cycles [42]. These batteries have high energy and power density compared to other batteries, and are, as a result, compact. Although lithium-ion batteries are primarily used for consumer electronics and EV's, they can play an important role in utility-scale energy storage operations such as frequency regulation. Their short discharge cycle (less than four hours) and high power performance make them optimal for this ancillary service operation. For lithium-ion technologies to compete at grid-scale they must improve in two important areas: duration and durability; that is, they must be able to maintain a longer discharge (several hours of energy to the grid at a time) and be able to last for over a decade, despite daily deep discharges [49].

AES Energy Storage has made recent headlines with the first deployment of Advancion 4, based on lithium-ion battery technology. This alternative to peaking power plants offers smart and cost-competitive energy storage for grid-scale use. By mid 2017, AES plans to complete a 10 MW system connected to India's grid, to provide backup power and to aid the integration of RES to the regional grid [49]. At Tesla's annual shareholder meeting on May 31, 2016, CEO Elon Musk announced that the Gigafactory could theoretically triple the total expected battery output to 105 GWh of cells and 150 GWh of battery packs (three times the current worldwide lithium-ion battery production) [50].

	Scalability	Flexibility	kW-kWh independent	Safety issue
Redox flow	High	High	Yes	Low
Adv. lead-acid	Good	Good	No	Low
Lithium-ion	High	Good	No	Mild
Sodium sulfur	High	Good	No	Mild

Table 3.1: Comparison between four various types of batteries [47].

3.3 Flow batteries

Flow batteries have the potential to provide longer-duration energy storage at low cost, two valuable features for utility-scale storage. The energy capacity is dependent on the volume of electrolyte, which is stored externally in tanks and pumped past a membrane between two electrodes. Pumps are used to circulate the electrolyte from the tank to the reaction stack containing the electrodes. By adding more tanks to the system, energy capacity can readily be increased [41]. On the other hand, the power is dependent on the size of the stack of electrochemical cells. As a result, flow batteries have significant design flexibility, both the power capability and the energy capacity can be independently adjusted to meet the needs of the desired load or generating asset [45].

The performance of flow batteries is typically not affected by overcharge or discharge, even when a large part of the energy capacity is used (deep discharge). Currently, the most promising chemistries for flow batteries include vanadium redox and zinc bromine redox. The former is the most researched flow battery and the closest to commercialization. UniEnergy Technologies (UET), a startup that provides flow batteries, received USD 25 million late last year during its second round of funding. The vice president of UET, Russ Weed, claims that it's vanadium redox battery is effective in microgrids, commercial and industrial applications, as well as utility applications. He expects the cost of storage to be between USD 700/kWh and USD 800/kWh; however, in the future, economies of scale will allow costs to fall to USD 500/kWh [48]. Installations of flow batteries have, however, not been widely deployed, due to past problems, such as premature degradation and high costs. The lower round-trip efficiency (70-80%) compared to lithium-ion (90%), as well as the high cost of pumps and pipelines for the electrolyte (which is prone to leaking), have hindered widespread adoption of this technology [41]. Nevertheless, companies continue to invest in flow batteries because of their potential and proven abilities in a range of applications. Economies of scale will lower the batteries' cost and allow them to be competitive with other battery technologies.

3.4 Advanced lead-acid

Advanced lead-acid batteries have found a niche in power-intensive applications, such as frequency response and smoothing. Recent developments of advanced lead-acid technology consist of carbon in one or both of the electrodes. When up to 40% of activated carbon is added to the electrode, the lifetime of the battery is significantly prolonged. Disadvantages of advanced lead-acid batteries include short life cycles, slow charging, and maintenance requirements. As a result, in order for advanced lead-acid batteries to be competitive with other types of batteries, their lifetime must be improved and their cost reduced. New lead-acid technologies include the CSIRO Ultrabattery, which can be used for EV's, RES storage, remote area power supply, and emergency backup power [52]. It offers high rate charge acceptance and is competitive with other battery technologies in terms of endurance, efficiency, and power handling. The energy storage company Ecoult has commercialized the Ultrabattery, which has applications such as power smoothing and load shifting, and can aid in the integration of intermittent RES. In addition, CSIRO's Ultrabattery has been used in the Honda Odyessey hybrid model [51].

3.5 Aluminum-ion batteries

A new battery technology that is yet to be commercialized uses aluminum as its anode and a specialized graphite foam as its cathode. In 2015, researchers at Stanford University developed an aluminum-ion battery that many considered a breakthrough in battery technology. According to these researchers, aluminum-ion batteries appear to have several advantages over lithium-ion batteries, which are predominantly used in electronic devices as well as EV's. First off, the Stanford researchers showed that their battery could not catch fire by drilling a hole through the battery while it was delivering electricity. Lithium-ion batteries have a tendency to catch fire and can therefore be a safety risk. The researches claimed that their battery prototype could fully charge itself in one minute, multiple times faster than lithium-ion batteries whose charging times are several hours. However, the energy capacity of the tested battery was not disclosed. The aluminum-ion batteries are capable of completing 7.500 charge cycles with no loss of capacity compared to lithium-ion's 1000 cycles. It is worth mentioning that these batteries could be competitively priced because aluminum is more abundant and, as a result, less expensive than lithium [76]. The Stanford researchers' prototype can be seen in figure 3.2.

The aluminum-ion battery has several disadvantages. According to the Scientific American, the energy density of the aluminum-ion battery is only one-fourth that of a typical lithium-ion battery (approximately 40 Wh/kg versus 160 Wh/kg). This implies that powering an electronic device or an electric vehicle with an aluminum-ion battery would require a battery four times as heavy as a lithium-ion battery with the same energy density [78]. Improving the cathode material, however, could increase the voltage and the energy density. Despite the negative aspects of aluminum-ion batteries, researchers are optimistic about their ability to serve the grid and aid in the integration of RES. They are inexpensive and can rapidly and repeatedly cycle through charges without affecting performance [76]. Their high power and ability to charge/discharge thousands of times without failing make them ideal candidates for providing balancing and reserve power to the grid. One should not expect this battery to penetrate the electronics or EV markets any time soon due to the significant weight increases that would be required to achieve the same performance [78]. The ALION European Horizon 2020 project was launched in June 2015 to develop a prototype of an aluminum-ion battery for energy storage application in decentralized electricity generation sources. The ALION prjoect seeks to use an integral approach consisting of electroactive materials, robust ionic liquid-based electrolytes, and current cell and battery concepts. The final product of this project is expected to be low cost with improved performance, reliability, and safety compared to other energy storage technologies [79].

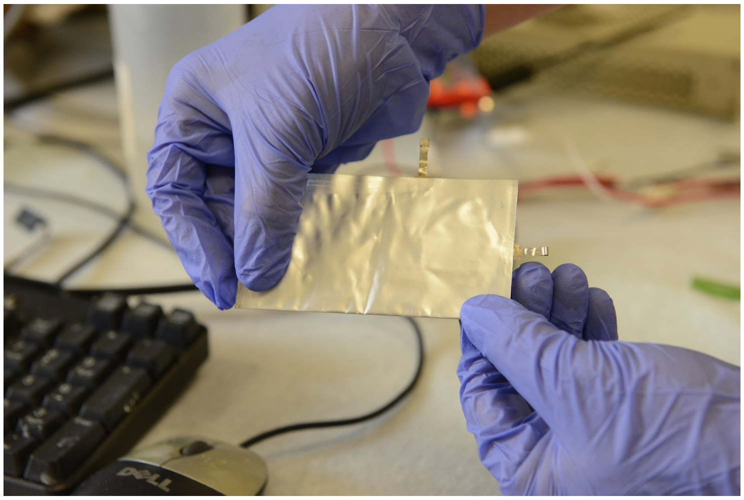


Figure 3.2: A prototype of the aluminum-ion battery produced by Stanford researchers. The battery is bendable and inflammable.

Chapter 4

Liquid Metal Batteries

Two problems with current solid-state battery technology are loss of significant capacity over time and mechanical degradation. MIT researchers are developing low-cost, efficient, liquid metal batteries (LMB's) that can be used to store energy on the grid. As stated before, the large-scale use of intermittent generating sources, such as solar and wind, will necessitate the ability to store large amounts of energy on the grid. This type of storage would eliminate the need to maintain extra generating capacity and allow for quick responses by operators during peak load hours [13].

LMB's are expected to penetrate several electricity markets. One significant application of these batteries would be for bulk storage, that is, storing energy generated at low demand hours and releasing it during peak demand hours [24]. In addition, LMB's would play a crucial role in ancillary services, such as frequency regulation.

4.1 Benefits of liquid metal batteries

Long operational lifetimes, reliability, and low manufacturing and material costs are crucial battery traits for grid energy storage. In order to meet this criteria, MIT professor Donald Sadoway investigated whether it were possible to reverse the well-known aluminum smelting process. He proposed the liquid metal battery: one similar to conventional batteries, however, consisting of liquid electrodes and electrolytes.

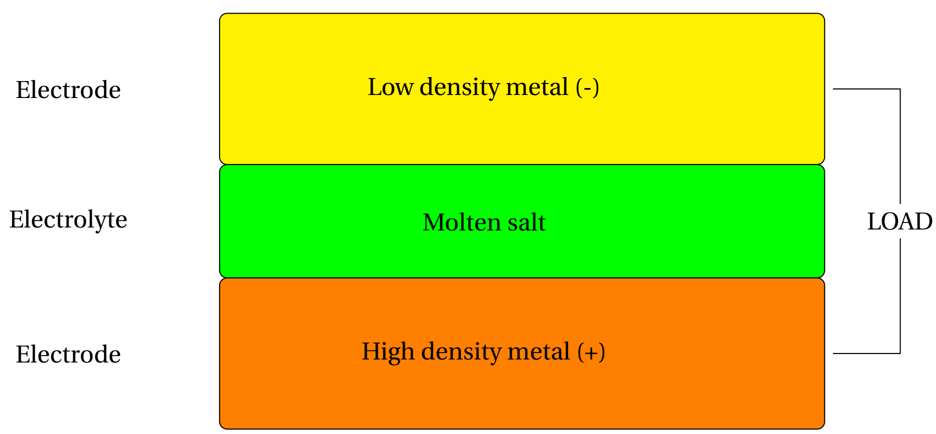


Figure 4.1: Above is a diagram of the basic components of a liquid metal battery. Electrons flow from the upper to the lower electrode through the electrolyte.

The top layer is a low density liquid metal that readily releases electrons while the bottom layer is a high density liquid metal that accepts those electrons. Between the electrodes is the electrolyte, a molten salt that transfers charged particles without mixing with the other layers. Solid electrodes in conventional batteries are prone to mechanical degradation, due to the stresses involved; however, liquid metal electrodes do not take on any stresses (cannot crack), and, hence, the lifetime of the battery is prolonged significantly. Furthermore, it may be possible to build giant LMB's using 50-100 fewer cells than with conventional batteries, hence, reducing both cost and complexity [24].

Traditional electrochemical batteries have not seen widespread deployment, even though they are available for commercial applications. Their energy density, power performance, lifetime, charging capabilities, safety, and costs have hampered their large-scale commercialization. Lithium-ion batteries are best suited for short discharges but struggle with deep discharges. Sodium-sulfur batteries can maintain longer discharges than lithium-ion batteries, but trail slightly in energy and power capacity. On the other hand, lead acid batteries are inexpensive, but their low energy density and short cycle time impede large-scale commercialization. LMB's are expected to be inexpensive, long-lasting, energy dense, and capable of large-scale storage on the grid, characteristics that could revolutionize battery technology.

4.2 Development of the battery

One of the biggest challenges Sadoway faced was choosing the right materials, due to the lack of research in the field of liquid metal batteries. The materials had to be abundant, long-lasting, and inexpensive. Sadoway and his researchers began by choosing magnesium as the top electrode, antimony as the bottom electrode, and magnesium chloride for the electrolyte to create working prototypes of their product. For this combination, current is produced when magnesium (Mg) gives off two electrons to produce magnesium ion (Mg^{2+}), which subsequently accepts two electrons from the antimony to form an alloy ($Mg - Sb$). However, the high operating temperature of 700°C was a problem because of the energy needed to achieve that temperature and the degradation to secondary components. After extensive experimentation, the researchers discovered that they could maintain the high voltage even when they added significant amounts of lead to the antimony (80% led). This effectively lowered the melting temperature by hundreds of degrees. Importantly, the battery is able to maintain the elevated operating temperature from the heat formation during charging and discharging [21]. Ambri, the startup company that Sadoway and his researchers founded in 2010, anticipated that the commercial product would start shipping in early 2016, but a problem with the battery seal has impeded the first shipment of the product. This seal is needed to keep air from leaking into individual cells and must withstand the high temperatures of the battery. Once this final engineering challenge is overcome, production of the commercial battery can begin [13]. Although some researchers express concerns over the efficiency of the batteries, specifically the 2% store charge that is lost each discharge, many are optimistic about LMB's deployment for grid energy storage [22].

4.3 Practical applications and suitability for Iceland

Liquid metal batteries have the potential of storing large amounts of energy and the ability to deliver energy at a fast rate. An automating process to aggregate many cells into a large-battery format is yet to be developed, however progress with these types of batteries has confirmed Sadoway's thesis that liquid metal batteries have superior performance and far longer lifetimes than conventional batteries. Although theses batteries cannot be used in vehicles due to their large size and high operating temperatures, the high storage capacity and long life cycle make liquid metal batteries ideal for load levelling and integration of intermittent RES to the power grid.

In the case of increased or decreased load on the grid, the system operator relies on ancillary services to regulate the short-term frequency deviations. Due to the lag in the governors of the generators, it is vital that frequency regulators respond immediately to meet the power requirements. Liquid metal batteries' ability to store energy from intermittent energy sources would be able to respond immediately to these fluctuations in supply and demand. LMB's will play a crucial role during outages and during peaks in

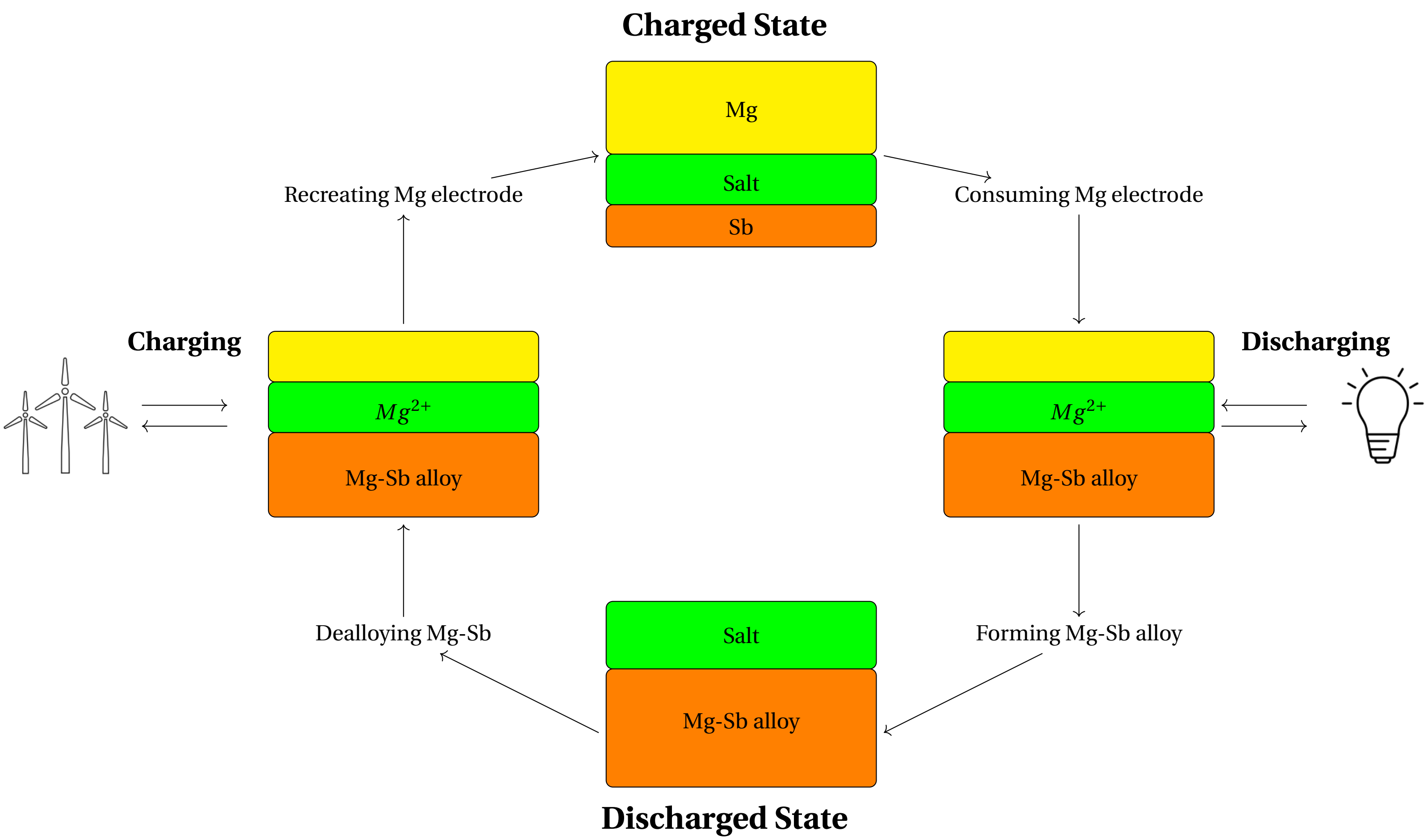


Figure 4.2: The charging cycle of a liquid metal battery [20].

power usage because of their quick response times and their ability to store large amounts of energy. These batteries would significantly increase the efficiency of grid operations; they would diminish the need to maintain back-up generating capacity, which is expensive and seldom used [13].

As Iceland adopts more intermittent RES, the demand for energy storage will increase. Landsvirkjun currently operates two windmills in the region Hafið, each with a power output of 900 kW. We, however, plan to construct a 200 MW wind farm in this area. Landsvirkjun has proposed two areas for the wind farm with either fifty-eight windmills, each with a power output of 3.5 MW or eighty windmills, each with a power output of 2.5 MW. Battery technology would be completely unnecessary because of the country's access to hydro power. During periods of strong winds, the hydro power plants would reduce their production and increase it again when contribution from the wind farm decreased. Batteries in general would suit smaller-scale operations in Iceland better where there is no access to hydro power.

4.4 Cost

Sadoway expects the cost per kilowatt hour of energy produced to be around USD 500, which is significantly higher than the USD 100 rate that is estimated to allow for large-scale adoption of this technology. However, because of the lack of moving parts in the LMB's and the liquid nature of the electrode, maintenance costs are very low. Lithium-ion batteries are currently priced at double what LMB's are expected to cost and are prone to degradation and significantly shorter lifespans. Some, however, are adamant about lithium-ion's potential as a competitive energy storage technology on the grid [22]. As of 2014, lithium-ion batteries for utility-scale applications were valued at USD 550 per kilowatt-hour. However, the price is expected to decrease over the coming years and is projected to be as low as USD 200 per kilowatt-hour by 2020. In addition, flow batteries are expected to experience a large decrease in price in the future. Their estimated value in 2020 is USD 350 per kilowatt-hour [41]. For liquid metal batteries to be competitive on the utility-scale battery market, the development of a low-cost manufacturing process will be critical.

Chapter 5

Pumped-Storage

The rise of intermittent generation has accelerated the construction of pumped-storage plants. Hydropower allows for the storage of water in the form of potential energy which can be released during peak demand when energy prices are highest. Pumped-storage plants take advantage of the lower energy prices during off-peak times, such as night, to pump the water from the lower to the upper reservoir. Although these plants consume more energy than they produce, they are able to profit by delivering power during peak demand hours and consuming energy during off-peak hours when energy is inexpensive. Nuclear and coal powered plants are most efficient when run continuously and are not shut down at night, resulting in the large energy price difference between day and night. Natural factors dictate for the most part energy production in dams and windmills, hence, the only option other than storing the energy is selling it at a lower price during low demand hours. The largest disadvantages to pumped-storage are the geographical constraints, necessitating a height difference between two bodies of water, and high capital costs. However, pumped-storage facilities are highly efficient (≈ 80%) and play a significant role in balancing the load on the grid, peak shaving, as well as providing ancillary services. Pumped-storage facilities are able to respond within seconds to large load changes, making them particularly valuable. They reduce the need for peaking plants, which are expensive to run because of their dependence of fossil fuels. Figure 5.1 shows the components and functionality of a typical pumped-storage facility.

5.1 Development

Commercial interest in pumped-storage plants has risen globally in recent years as governments have implemented more regulations on carbon emissions in response to climate change. By 2020, it is expected that over 100 pumped-storage plants with 74 GW capacities will be in operation. Multiple European countries, including Spain, Switzerland, and Austria, are adding pumped-storage capacity to adapt to the increase in intermittent RES. China has the most drastic plan, which includes quadrupling its current pumped-storage installations to a capacity of 100 GW by 2025. The U.S., which issued two licences in 2014 for the construction of pumped-storage plants, plans to bolster its existing pumped-storage capacity. Japan leads the world in pumped-storage capacity with over 27 GW and plans to further increase its energy capacity by developing additional plants [29].

5.2 Variable-speed pumped-storage

Traditional reversible Francis pump-turbines act as a turbine in one direction and as a pump in the other and are the most common technologies used in pumped-storage plants. Variable-speed pumped-storage was first implemented in the early 1990's in Japan and was quickly adopted by Europeans several years later [29]. While in pumping mode, variable speed technology allows the power consumed to be varied

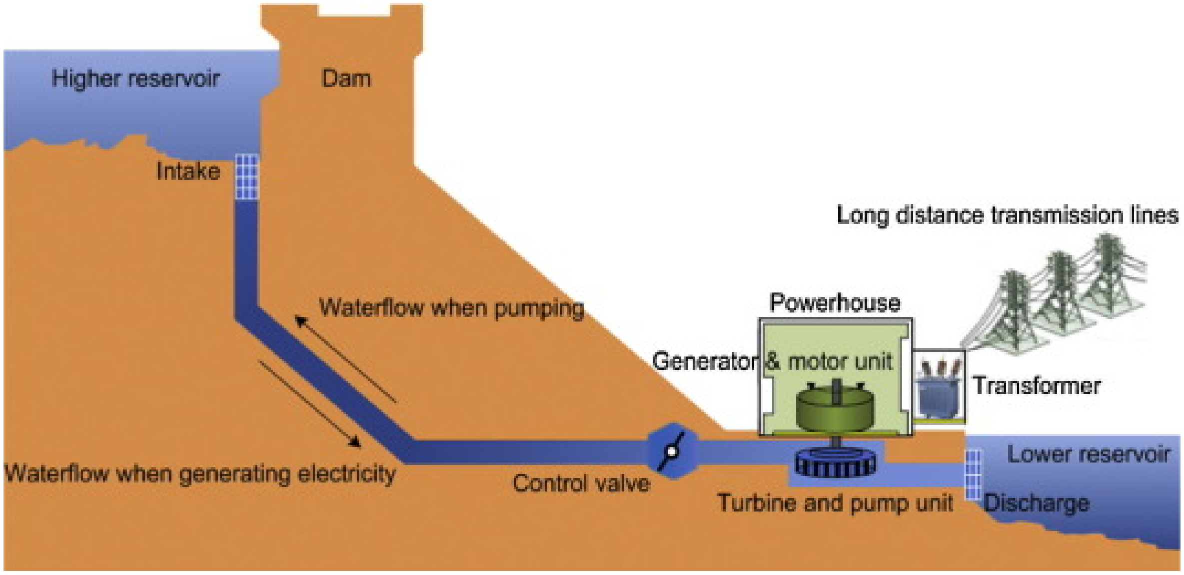


Figure 5.1: Pumped-storage process [32].

over a range of outputs [31]. Its flexibility is especially useful for compensating for fluctuations in power from intermittent RES. As more and more pumped-storage plants rely on intermittent RES to pump the water back to the upper reservoir, there is greater demand for pump-turbines that are capable of frequency regulation to allow for greater efficiency. Fixed-speed pump-turbines, on the other hand, only have two settings, full power and turned off, limiting their flexibility [28]. In addition, variable-speed technologies have faster response and turnaround times than fixed-speed technologies. The only downside to this technology over fixed-speed turbine-pumps is the increased cost; however, this expense is justifiable.

5.3 Seawater pumped-storage

As mentioned before, a large disadvantage to traditional pumped-storage plants is that they are very site-specific. To avoid this problem, the seawater pumped-storage plant was introduced. This form of energy storage is almost identical to traditional pumped-storage plants; however, the ocean acts as the lower reservoir. Currently, there is only one such plant operating in the world: the Okinawa Yanbaru Seawater Pumped-Storage Plant. This plant pumps water from the Philippine Ocean to an artificial upper reservoir, roughly 150 meters above sea level [33]. An aerial view of the plant can be seen in figure 5.2.

A 480 MW seawater pumped-storage plant has been proposed in Glinsk, Ireland. This plant would use roughly one-third of the excess wind energy to power the pump-turbines. Ireland plans to add 5000 MW of wind power by 2020. The disadvantages, however, of seawater pumped-storage plants are the corrosion that results from the seawater and the adhesion of marine organisms to the pipes. However, engineers have discovered that using fiberglass reinforced plastic for the penstock and austenite stainless steel for the turbine minimizes the corrosive effects of the seawater [33].

Figure 5.2: Okinawa Yanbaru Seawater Pumped-Storage Plant, which has been operating since 1999 [33].

Chapter 6

Compressed Air Energy Storage

Another type of large-scale energy storage is in the form of potential energy in compressed gas. As with pumped-storage, compressed air energy storage (CAES) takes advantage of low energy prices during low demand hours and sells the electricity at a higher price during peak hours. Hence, the primary ancillary service that CAES provides to the grid is load leveling [35]. CAES technology has the potential tp play a crucial role in the adoption of intermittent RES, whose fluctuating power output necessitates the large-scale storage of energy. Similar to pumped-storage plants, the full capacity of a CAES plant is available within minutes. CAES plants diminish the need for reserve power plants that use fossil fuels because they have sufficient balancing capacity and can act as short-term reserves [34]. The installed capacity of a commercial CAES plant ranges from 35-300 MW [35].

6.1 Operating CAES plants

There are only two CAES plants in operation today, one in Huntorf, Germany and the other in McIntosh, Alabama. Both of these plants use the diabatic process, as do most of the new plants that are being planned. However, the German energy company RWE is developing an adiabatic plant called Der Adiabate Druckluftspeicher fur die Elektrizitatsversorgung (ADELE) and plans to begin operations in 2018 [36]. ADELE will be integrated with a wind farm and use the surplus electricity to store energy until demand rises. The diabatic and adiabatic processes are described in greater detail below.

	Huntorf	**McIntosh**
Capacity (MW)	290	110
Efficiency	42%	54%
Reservoir type	Two salt dome caverns	Single salt dome cavern
Use	Load following and peak shaving	Peak shaving and spinning reserve
Reservoir pressure range (MPa)	4.8-6.6	4.5-7.4
Storage capacity (hours)	3-4	26

Table 6.1: Comparison between the two operating diabatic CAES plants [38, 40].

6.2 Diabatic process

When demand is low or an additional load is needed for balancing the grid, energy from wind turbines or other intermittent RES's is used to power a motor which, in return, powers electrically driven compressors. These multistage compressors use inter and after coolers to reduce the temperature of the compressed gas to a little over $40°C$. The compressed air is forwarded to an underground salt cavern, where it is stored until the demand for electricity is high. The cooled air is then heated by a combustor using natural gas to expand the air as it is fed into a turbine. The turbine turns the generator and electricity is produced for the grid. The high power density and system flexibility of the diabatic process have led to its commercial implementation. The general process is shown in figure 6.1.

6.3 Adiabatic process

Adiabatic plants recover the heat that is produced during compression to reheat the gas before it enters the turbines. As a result, this type of plant has a much higher efficiency ($\approx 70\%$) than its diabatic cousin ($\approx 42-54\%$). The compressors send hot, compressed air to large heat accumulators (vessels) that are well insulated to prevent losses, thus, maintaining a high efficiency. The compressed air is cooled down and forwarded to an underground salt cavern, where it is stored until peak hours of the day. To release the stored energy, the cool air is heated, using the thermal energy recovered from the compressors, and directed into the turbine, which turns the generator and produces electricity. Here, there is no need for natural gas to heat up the air, thus, increasing the efficiency of the process. Instead, heat exchangers are used to cool the air that leaves the compressors and to heat the air that enters the turbines [38].

For both methods, a large storage capacity is crucial, due to the low storage density. Salt caverns are particularly appropriate for this type of storage, because they maintain pressure and there is no reaction between the salt host and the oxygen in the air. Natural aquifers and depleted natural gas fields are potentially viable options for CAES reservoirs. Tests must be carried out, however, to ensure that there is neither oxygen depletion nor blockage in the pores of the reservoir. For depleted natural gas fields, the mixing of residual hydrocarbons with compressed air is problematic and must be assessed [36]. Similar to pumped-storage, CAES is site-dependent, meaning that it relies on a specific geography for operation.

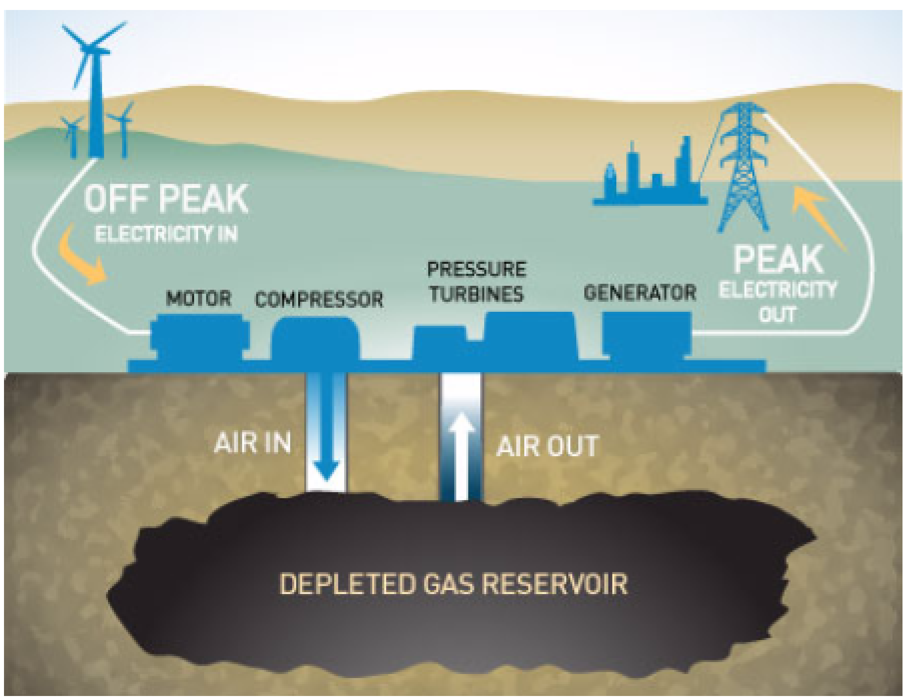


Figure 6.1: Compressed air energy storage process [37].

6.4 Development

Engineers must solve several technical challenges before an adiabatic plant starts operation. To begin with, a high pressure and high temperature compressor must be designed to withstand thermal stresses. In addition, the bearings and lubrication in the compressor must be able to withstand the immense heat ($> 600°C$). The ADELE plant is expected to have a capacity of 360 MWh and 90 MW of output power. Because the plant is expected to use surplus energy from wind power to power its compressors, this energy storage method would be emissions free [38]. It is important that CAES technologies be implemented in order to mature this form of energy storage.

Lightsail Energy, a company based in the United States, is currently developing an adiabatic compressed air energy storage (ACAES) power plant that uses a dense mist of water spray to absorb the heat energy of compression and provide it during expansion. The system is fully reversible; when energy is delivered, the air compressor becomes an expander, and the electric motor becomes a generator. The compressors could make use of inexpensive surplus solar and wind power to compress the air, and as a result be used to time-shift these intermittent RES. In this way, the storage could be used to time-shift solar and wind power. According to the company, this adiabatic plant has reached a maximum power of 250 kW with high thermodynamic efficiencies. The company claims that its first generation product will provide cheaper electricity than diesel generators, and that its second generation product will outmatch gas peaker power plants, hence, encouraging the universal adoption of RES [39]. The technology is still in the early stages of development and far from commercialization, so the claims should be taken with a grain of salt.

6.5 Efficiency

Conventional large-scale CAES plants rely on fossil fuels to reheat the gas prior to entering the turbines, resulting in CO_2 emissions. The McIntosh facility, however, uses a heat recuperator that recovers heat from the gas turbines to increase its efficiency. Fuel consumption is effectively reduced by over twenty percent and the efficiency climbs from roughly 42% to 54% [38]. As a result, the plant uses approximately one-third of the natural gas per kilowatt-hour that a combustion turbine consumes. Better yet, an ACAES plant would not depend on fossil fuels and, therefore, not produce any CO_2 emissions. A significant portion of ACAES's enviornmental impact is a result of the material-intensive thermal energy storage system.

Chapter 7

Thermal Storage

Thermal energy storage can be a valuable method to avoid the curtailment of energy from intermittent RES. Various forms of thermal energy storage exist, and some of the most prominent methods are discussed below.

7.1 Pumped-heat electrical storage

In 2005, a private engineering company called Isentropic was founded by an aerospace engineer named Johanthan Hower and two of his colleagues to develop the pumped-heat electrical storage (PHES) technology for grid-scale storage. PHES is a closed circuit process based on the first Ericsson cycle that stores energy as the temperature difference between hot and cold stores. This process involves two storage vessels, a cold store and a hot store, as well as a compressor, an expander, and a generator. The process is highly reversible and the direction of fluid flow depends on whether the system is charging or discharging. Energy is stored as the temperature difference between hot and cold stores. During this process, the working fluid, argon, begins at standard temperature and pressure at the top of the cold store. The gas flows to the adiabatic compressor, where the pressure and temperature rise to 12 bar and 500°C, using off-peak electricity. The pressurized, hot gas enters the top of the hot storage vessel and permeates the mineral particulate within the vessel, causing the gas to cool and the particulate to absorb the heat. As a warm front (region where the heat exchange is active) moves down the hot storage tank, the system charges itself. As the gas exits the hot storage vessel, it enters an expander, causing a drop in pressure and temperature to one bar and −150°C. The gas subsequently enters the cold storage vessel, where the gas warms as it moves through the mineral particulate. This causes a cold front to rise in the vessel, charging the system. Figure 7.1 shows the described charging cycle. At any point during the charging cycle, the system can be reversed to turn a generator and produce electrical energy [53]. The round-trip efficiency of PHES plants is 72-80%, roughly the efficiency of a pumped-storage plant [55]. However, unlike pumped-storage and CAES plants, PHES plants do not require specific geographies and can therefore be deployed at any location. In addition, the capital costs of a PHES plant is significantly lower than that of a pumped-storage facility.

Isentropic claims that it can achieve a levelized cost of storage of USD 35/MWh, lower than utility-scale batteries and pumped-storage technologies. If this is the case, PHES technology will be highly competitive as grid-scale energy storage systems. Since receiving USD 22 million, the company has been developing a 1.5 MW/6 MWh PHES storage unit, expected to serve the U.K. grid [54]. The response time of PHES systems is several minutes and, hence, address markets that are currently addressed by pumped-storage plants, such as voltage support. PHES plants are expected to produce power of 2-5 MW, however, when grouped units can produce gigawatt-scale installations [56]. According to Isentropic, in addition to low cost and high round-trip efficiency, their PHES technology is safe, environmentally inert, and has a long life and large number of cycles.

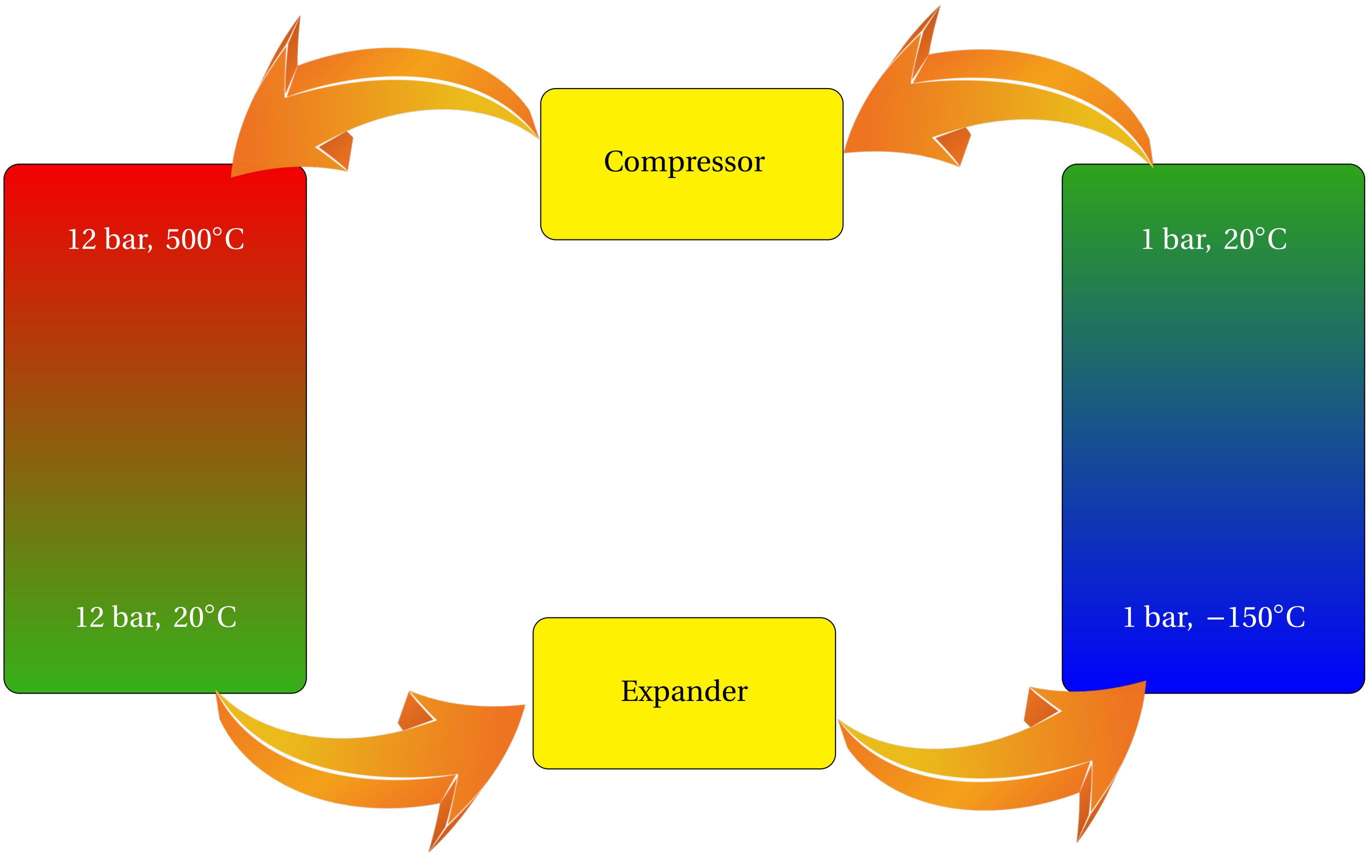


Figure 7.1: Charging process of PHES. The cycle is reversed to deliver power.

7.2 Liquid air energy storage

Liquid air energy storage (LAES), or cryogenic energy storage (CES), is a process by which air is cooled to liquid form and stored in a vessel until there is demand for electricity. When the air is warmed back up, the air expands and powers a turbine to create electricity. LAES allows for large-scale energy storage and a long operational lifetime (30+ years). This technology is able to use waste heat from its own and other processes to improve its efficiency and rely less on fossil fuels to generate heat. For example, the heat generated during the liquidation process can be used during the power recovery process, thus, improving efficiency. There is significant potential for large-scale energy storage because hundreds of liters of ambient air can be reduced down to several liters of liquid air. The LAES system consists of three stages: charging, storing, and discharging. During the charging stage, an air liquefier uses electricity to cool air to $-196°C$. The air is stored in large insulating vessels at low pressure, with gigawatt-scale energy storage potential. The equipment has already been globally deployed for bulk storage for liquid nitrogen, oxygen, and LNG. During the discharge stage, the liquid air from the vessels is pumped to high pressure. The air is heated to ambient temperature, which drives a turbine to produce power [56].

From 2011 to 2014, Highview Power tested a fully operational 350-kW/2.5-MWh LAES pilot plant that was connected to the U.K. grid and complied with all regulations. Depending on whether a new pre-commercial demonstration project shows promising results, Highview Power plans to build a gigaplant with 200 MW of power and an energy capacity of 1.2 GWh. The demonstration plant is scheduled to be operational in the first half of 2016 and will show how LAES can balance supply and demand, as well as provide support on the grid during peak demand in winter [57]. LAES does not have geographical restrictions like pumped-storage and CAES, making deployment easier and more convenient. These plants have gigawatt-scale potential, low cost per kilowatt, and are environmentally benign, making this technology particularly attractive for grid-level energy storage.

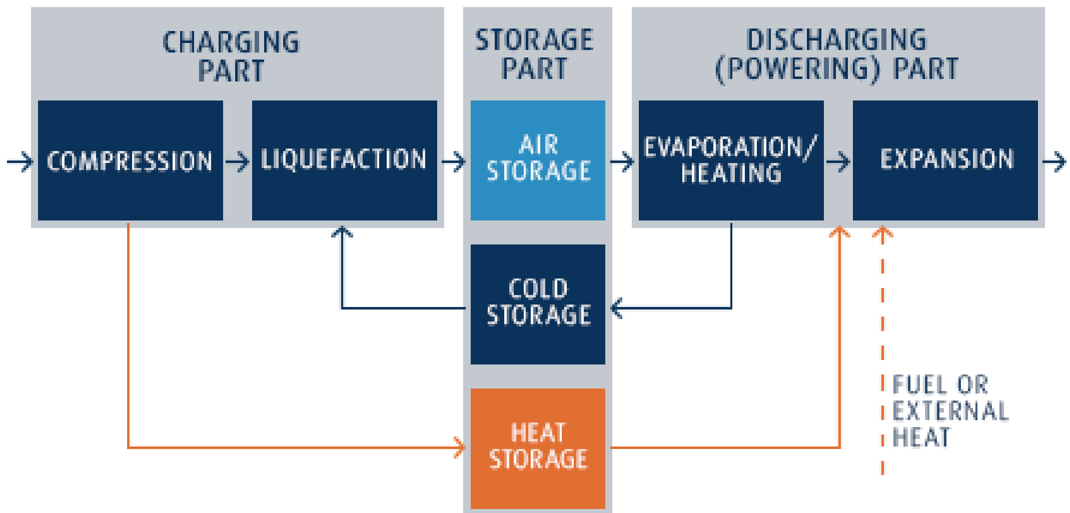


Figure 7.2: LAES three stage process [58].

7.3 Hydrogen energy storage

Hydrogen energy storage (HES) makes use of water electrolysis technology to store renewable energy on a large, long-term scale. HES stores grid electricity as hydrogen, which can then be converted back to electricity upon demand. There is incredible potential for HES to penetrate several markets, including ancillary services, fuel cell electric vehicles (FCEV's), material handling equipment (MHE), backup power supply, feedstock supply to refineries, and other industrial processes. Electrolysis units can provide ancillary services to grid operators by supplying regulations and ramping services. Various tests have shown that electrolyzers respond quickly enough to take part in electricity and ancillary service markets, such as contingency reserves, and regulation. In addition, the integration of HES with demand response has been investigated, which would allow HES to play an important role in a smart grid context by providing increased flexibility and resiliency [59].

Another significant market for hydrogen is FCEV. Although major automakers, such as Toyota and Hyundai, have produced relatively few light-duty FCEV's, these vehicles are expected to draw great demand in the medium- to long-term. California's policies supporting the installation of hydrogen refuelling stations has made it an early market for FCEV's. The National Research Council is optimistic regarding FCEV's contribution to the long-term light-duty electric vehicle fleet, predicting that FCEV costs will drop below those of hybrid EV's. Figure 7.3 show the past and estimated future percentage of FCEV's among the fleet of light-duty vehicles in California. A recent survey conducted by CARB estimated that by 2020, 18000 FCEV's will be in operation in California alone. The deployment of hydrogen FCEV's as a feasible alternative for

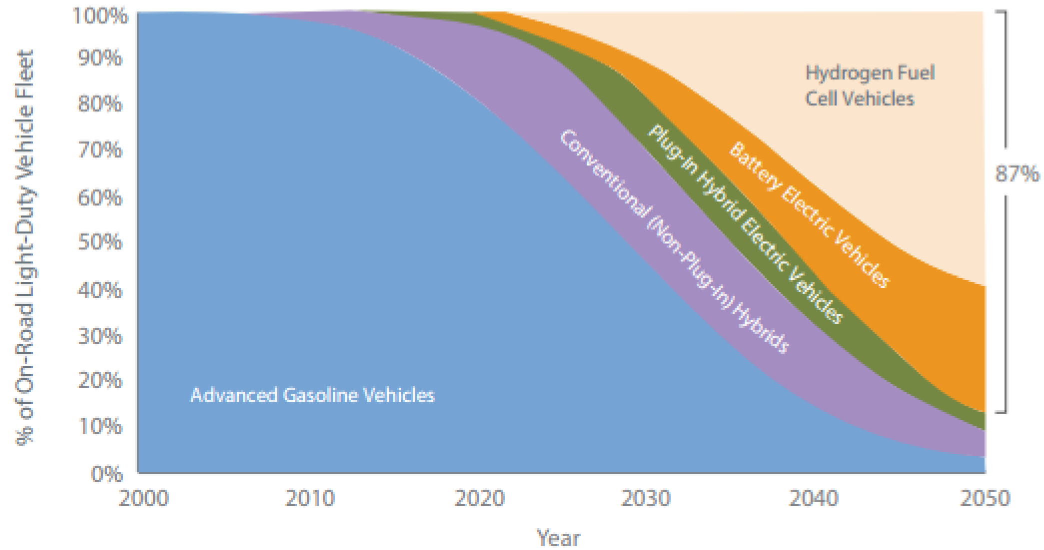


Figure 7.3: Percentage of light-duty vehicle fleet by year in California [59].

consumers may prove to be a difficult task. The cost of hydrogen at filling stations is expected to decrease slowly because of the costs associated with constructing a new infrastructure for hydrogen transportation, distribution, and retail sales. Economies of scale alone will not be sufficient in making FCEV's economically feasible. Instead, significant policy intervention, such as tax exemptions and subsides, would be essential to ramp up the FCEV market [42].

In the short-term, however, MHE (e.g. forklifts or airport tugs) is an emerging market that could benefit from the use of fuel cells, as opposed to other battery technologies, because of continuous operation at full power and quick refuel times. As a result, fuel cell MHE could significantly increase productivity while lowering labor costs. The market for MHE's has grown rapidly in recent years, especially in multi-shift warehouses.

Chapter 8

Kinetic Energy Storage

8.1 Flywheels

Recent advances in light-weight/high-strength composite materials, magnetic bearings, and power electronics technology has revived interest in flywheel energy storage. Flywheel energy storage systems (FESS) store energy in the form of kinetic energy, more specifically in a spinning rotor. Flywheels can achieve similar energy capacities to chemical batteries, but are non-toxic and can operate in a range of temperatures. As a result, they are less hazardous and more environmentally friendly than batteries and require less thermal control. Modern flywheels consist of magnetic bearings and are operated in a vacuum to

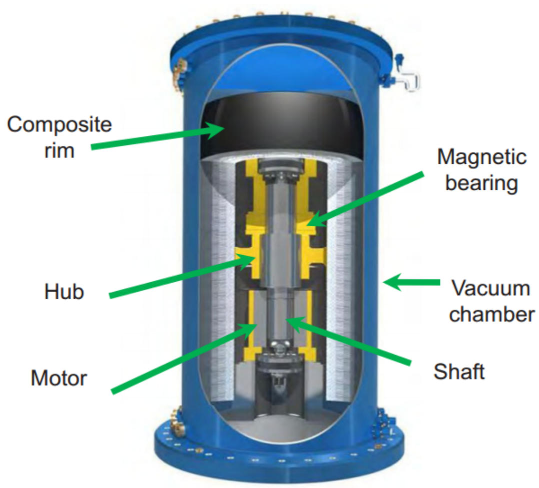


Figure 8.1: The primary components of a flywheel [60].

minimize frictional and drag effects. The rotor is made of carbon composites for high strength and minimal weight, allowing for very high rotational speeds. The flywheel is connected to a motor/generator that is connected to the grid through power electronics. The motor uses electricity to spin the the rotor at high speeds, which then produces electricity for later use by spinning the generator. Flywheels are long lasting, (capable of 100.000 to 175.000 deep discharge cycles), and require little to no maintenance. In addition, advanced flywheels have very fast response and ramp rates, meaning they can go from full discharge to full charge in a matter of seconds. They have found a niche in aerospace and uninterrupted power supply

(UPS) applications [60]. NASA's advanced flywheel system is in development and has the potential of penetrating the following commercial applications: Grid energy storage for power plants, energy storage for remote bases, load-leveling for aircraft or automotive purposes, and power quality improvement [61]. Modern flywheels could complement intermittent RES by levelizing supply with demand on the grid. This would effectively diminish the need to use peaker power plants that depend on fossil fuels and would, hence, be more cost effective and less environmentally adverse [61].

NASA agreed to a pre-patent licensing agreement with the energy solutions provider Power Tree Corp. of Miami, FL to design, produce, and operate several electric power management systems. This allows Power Tree to commercialize the next-generation G6 advanced flywheel for a variety of grid and industrial applications. Among these applications are demand side management functions and voltage and frequency regulation services to aid in grid stability as more RES are integrated with the grid.

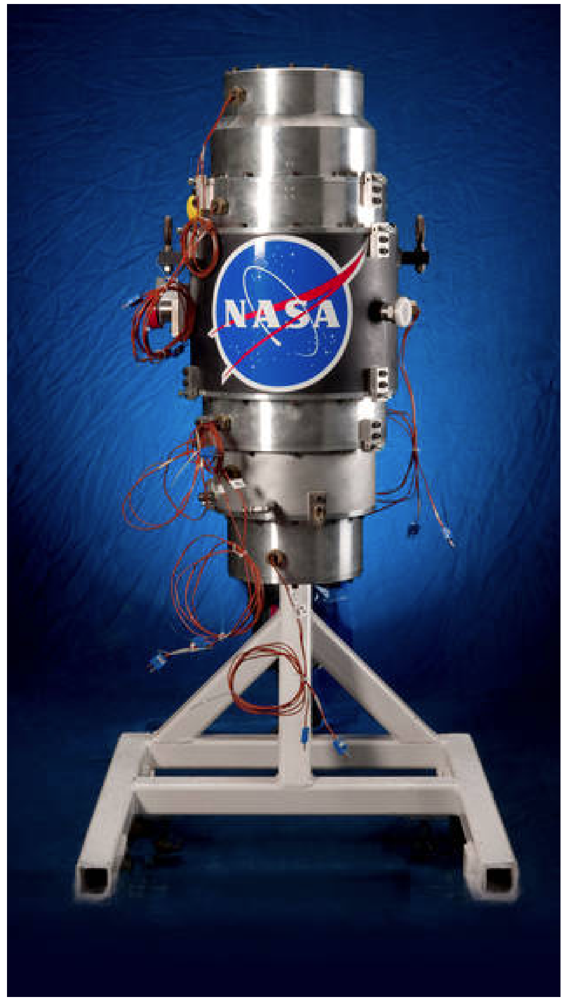


Figure 8.2: The G6 advanced flywheel designed and developed by NASA [62].

Beacon Power, a flywheel-based energy storage company, built a 20 MW energy storage plant in New York in 2011, which delivers frequency regulation services to the grid. This relatively high power is obtained by connecting 200 flywheels in parallel, which allows them to produce 20 MW in up- and down-regulation. After two years of commercial operation, the flywheel plant has provided over 250.000 MWh of frequency regulation services. A recent order by the Federal Energy Regulatory Commission (FERC) has demanded that interstate grid operators install market systems that account for the speed of the responding source. As a result, fast responding sources, such as flywheels and batteries, will be compensated more than slow responding sources, such as those dependent on fossil fuels [63]. The instantaneous response of flywheels, over one-hundred times faster than traditional generating sources, will allow for increased earnings and a significant competitive edge.

The flywheel plant in New York has achieved a system availability of 97%, outperforming conventional generators performing frequency regulation. This plant has demonstrated roughly 4.000 full charge/discharge cycles per year without reductions in performance and very low operating costs. The cost per kWh for flywheel energy storage is competitive with fast assets, such as grid-scale batteries, and is expected to decrease with economies of scale. It is the long life cycle, high performance, and remarkable robustness of flywheels that make them competitive assets at the grid-scale level [63].

Chapter 9

Gravitational Potential Energy with Solid Masses

9.1 Advanced Rail Energy Storage

Another mechanical solution to energy storage at the grid-scale level has recently been accepted by the Bureau of Land Management (BLM) for its proposed 50 MW/ 12.5 MWh energy storage system. The company Advanced Rail Energy Storage (ARES) uses a fleet of electric trains on an automated steel rail network to store and release energy. When there is low demand for energy, inexpensive electricity is used to power motors in the heavy train cars up a hill. During peak hours, when there is large demand for energy, the trains are sent down the hill and the motors act as generators, producing energy. The hill will have a slope of roughly eight degrees and the change in elevation is expected to be around 915 meters. The project will use 43 hectares (106 acres) of public land in Nevada and is expected to cost USD 55 million [64]. It is scheduled to begin construction in late 2017 or early 2018 and is expected to begin operations in 2019. This plant is intended to provide frequency and voltage regulation services to help stabilize the regional transmission grid and to aid in the integration of RES.

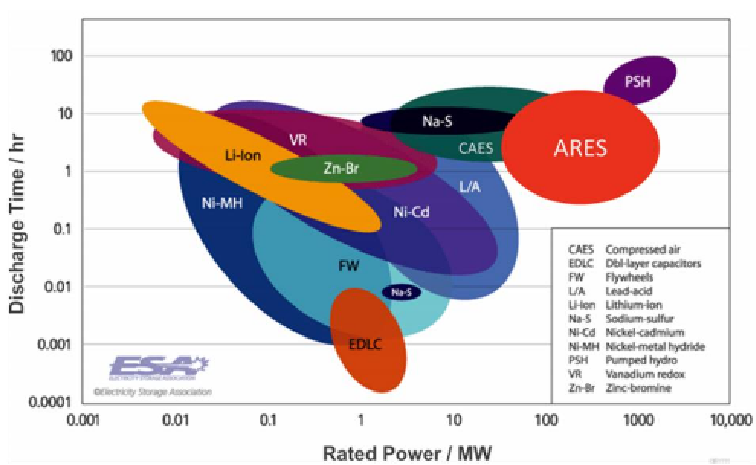
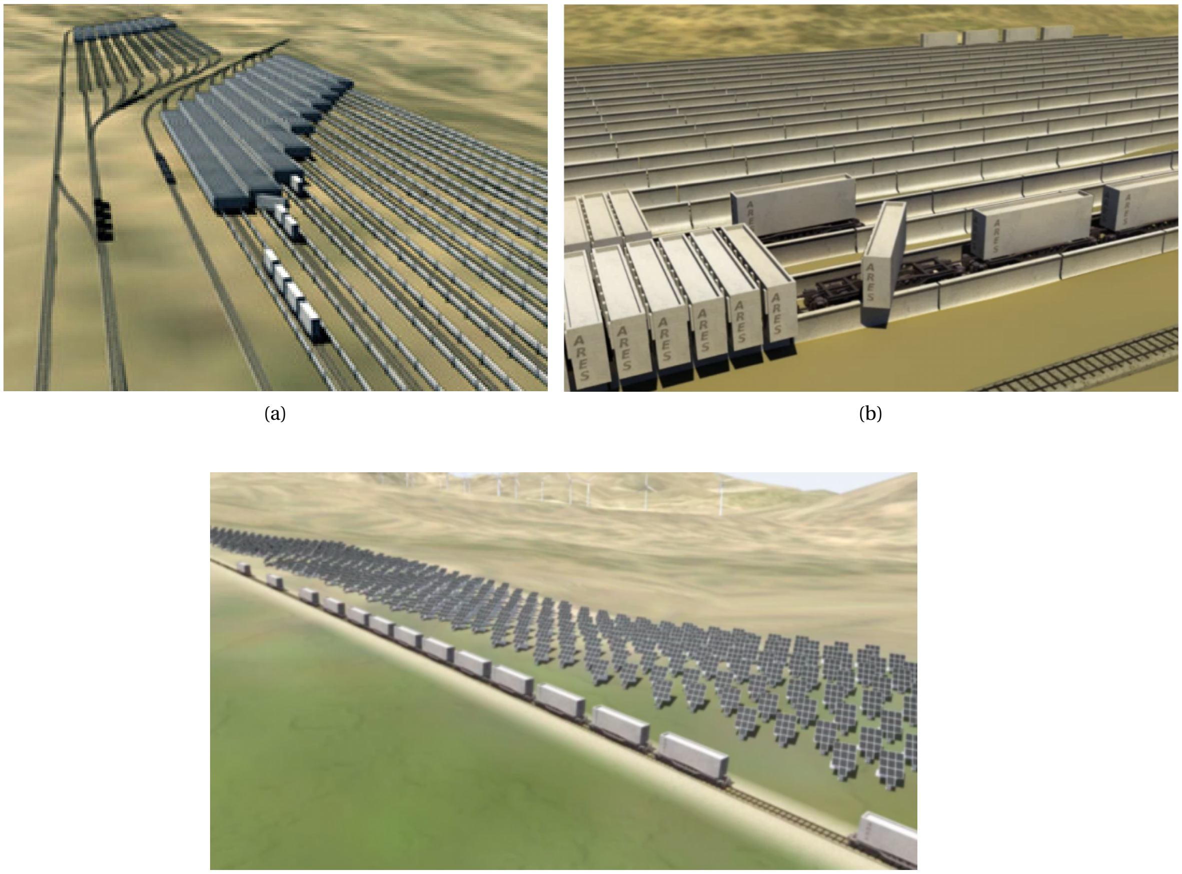


Figure 9.1: Graph showing discharge time as a function of power output [65].

ARES uses proven and mature technologies that have been around for many years and tested thoroughly. According to ARES, its technology has a lower life-cycle cost than batteries, a higher energy to power ratio than flywheels, and a faster ramp rate and higher efficiency than pumped-storage technology [66]. Figure 9.1 compares various forms of energy storage and shows that ARES is capable of discharging hundreds of megawatts of power over a period of several hours. Unlike pumped-storage, ARES is very scalable. It is difficult to find suitable geography for pumped-storage and CAES facilities,



(a) (b) (c)

Figure 9.2: Rendition of an ARES system shows (a) the rail system, (b) compact storage of the train cars, and (c) integration with solar panels to help power the train cars uphill [69].

and they are associated with high capital costs. ARES claims that its energy storage system's capital cost is approximately 60% that of a pumped-storage facility, but these costs vary significantly and make it difficult to generalize [67]. Although less site-specific than pumped-storage and CAES, ARES requires a large area with a hilly landscape and preferably an arid climate where there is large-scale deployment of solar and wind facilities. Similar to pumped-storage facilities, ARES systems last for 30-40 years. The storage capacity of ARES ranges from several hundred megawatt-hours to several gigawatt-hours, and the efficiency approaches 80% [69, 68]. Figure 9.2 shows a computer generated image of the ARES system in operation.

9.2 Heavy load energy storage

Heavy load energy storage (HLES) is based on the same principles as ARES: storing energy in the form of gravitational potential energy. A deep hole is drilled into the earth, similar to boreholes for geothermal fields, and a heavy load connected to a shaft is lowered down into the hole. As the load moves down, the shaft of the variable-speed generator rotates, and power is produced. During off-peak hours when electricity is cheap, the loads are heaved back up by motors to "recharge" the system. This form of energy storage would be highly scalable, that is, rows of these holes could be lined up, each row corresponding to a generator shaft (see figure 9.3). In addition, energy capacity could be increased by drilling deeper and/or increasing the number of holes. Power would be increased by allowing the loads to fall at a faster rate or by having several loads fall at the same time. The drilling technology to drill holes several kilometers deep is already available. An illustration of the matrix system of the loads and boreholes is shown in figure 9.4.

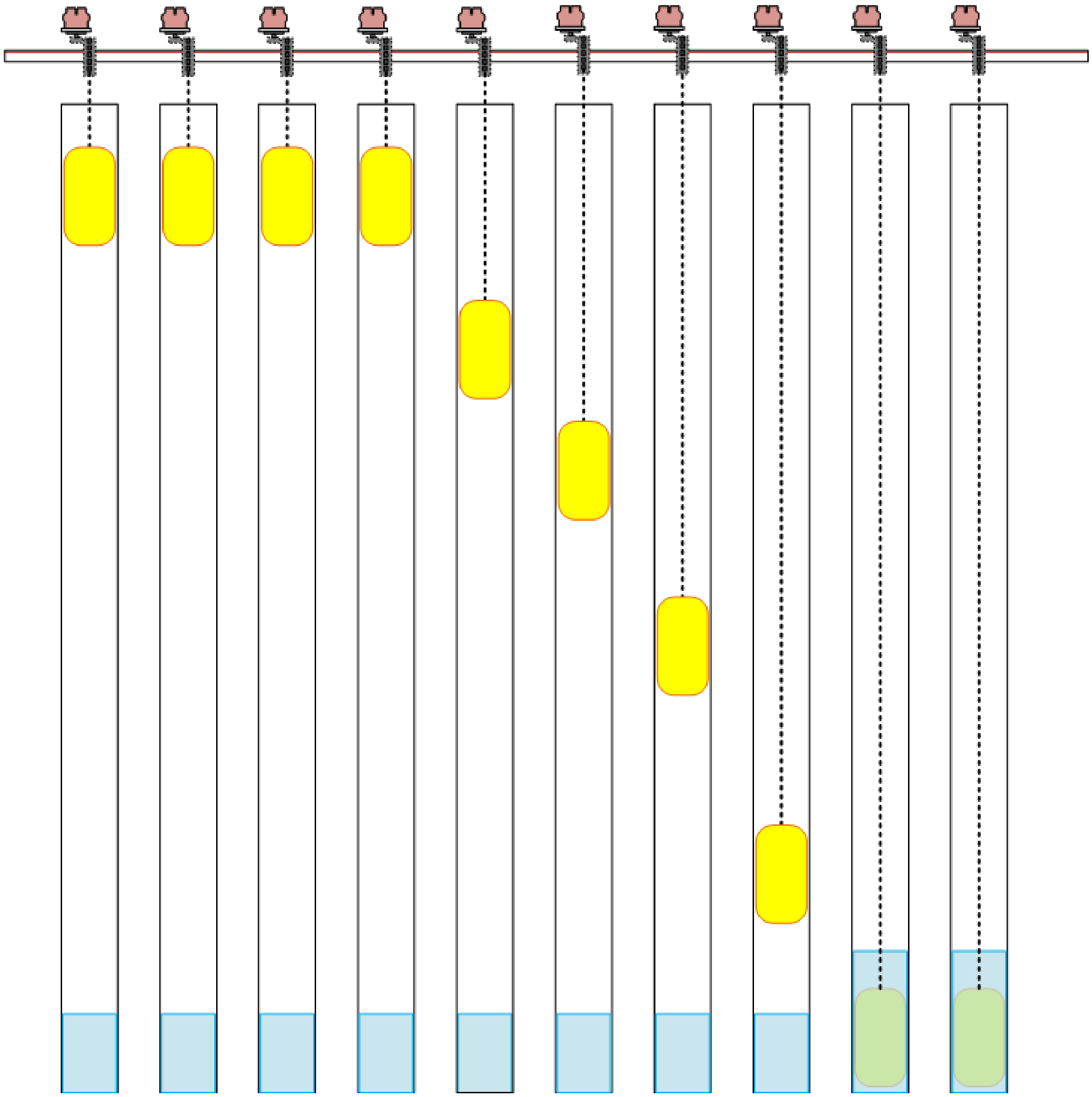


Figure 9.3: Diagram of a single row of loads and holes, each connected to the same generator shaft [*Image credit: Óskar H. Valtýsson*].

This method of energy storage has not yet been commercialized, but is very similar to ARES and other energy storage systems that rely on the potential energy of solid masses. This would be a relatively low cost, long lifetime, high capacity energy storage solution that could operate in a variety of climates. In addition, this method relies on proven technologies, such as motors and generators, making implementation easier. This mode of energy storage is not nearly as site-specific as pumped-storage or CAES, making it significantly more scalable. Assuming minimal frictional losses, the efficiency of this technology would theoretically be around 80%, similar to ARES and PHES. Using the potential energy of heavy loads offers a flexible and reliable way of storing excess energy from RES on the grid.

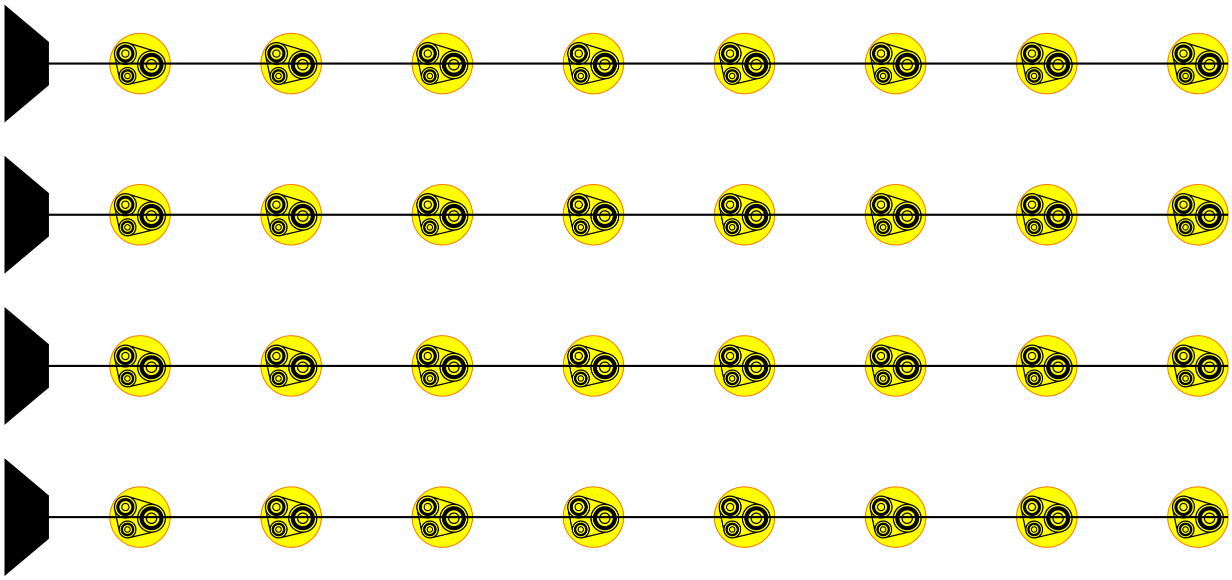


Figure 9.4: Matrix structure of boreholes as viewed from above. The black trapezoids represent generators.

Chapter 10

Supercapacitors

Despite a battery's relatively high energy density, a large disadvantage is its long charging time. Conventional capacitors, on the other hand, can charge almost instantly and have a high power density, but lack in energy density. Supercapacitors share the high power density but have higher energy densities compared to conventional capacitors. The lack of chemical reactions on the electrodes in supercapacitors allows for very low internal resistance and results in negligible energy loss through heat, making the efficiency around 95% [71, 73]. The electrostatic nature of supercapacitors gives them a long cycle life, meaning they can charge/discharge millions of times with limited effects on performance. Over a period of ten years, the capacity of a supercapacitor decreases from 100% to roughly 80%. A disadvantage of supercapacitors is that they withstand relatively low voltage limits, usually around 2-3 volts. Higher voltages are obtained by connecting several supercapacitors in series. Too high voltages (over ≈ 3 volts), however, will shorten the cycle life of the supercapacitor. Another disadvantage is the high self-discharge rate compared to batteries; the supercapacitor discharges 50-100% over a one month period while lead and lithium based batteries discharge only about 5% [72].

10.1 Development

Research on supercapacitors in recent years has emphasized improving energy capacity. The development of composite and nanostructured materials is thought to increase energy capacity in superconductors. Researchers suggest that instead of using the usual porous carbon-based materials, carbon nanotubes may lead to energy densities of 60 Wh/kg and power densities of 100 kW/kg. Nanostructured carbon materials' high electrical conductivity, high specific surface area, corrosion resistance, high temperature stability, and tunable porous structures make them ideal candidates for electrode materials in supercapacitors. In addition, nanostructured carbon materials have longer cycle stability and a lower cost. Figure 10.1 shows the cost per kilojoule and per farad from 1994 to 2012. Figure 10.2 compares the specific energy versus specific power for four energy storage technologies.

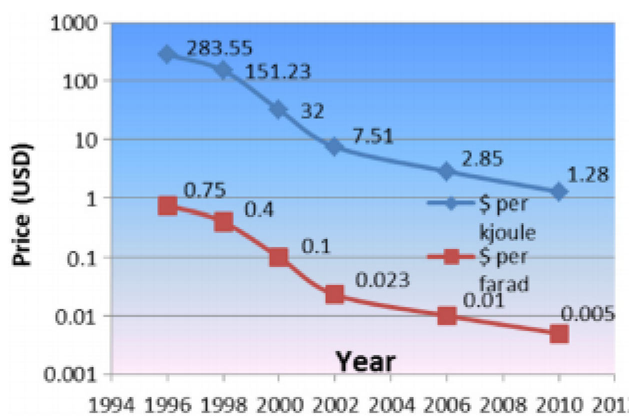


Figure 10.1: Graph showing costs of supercapacitors per kilojoule and per farad [75].

As the graph shows, batteries excel in energy density but their low power densities make them unsuitable for high power demanding services such as regenerative breaking and load leveling. While supercapacitors have inferior energy density compared to batteries, they exhibit excellent high cycle stability and power densities [75].

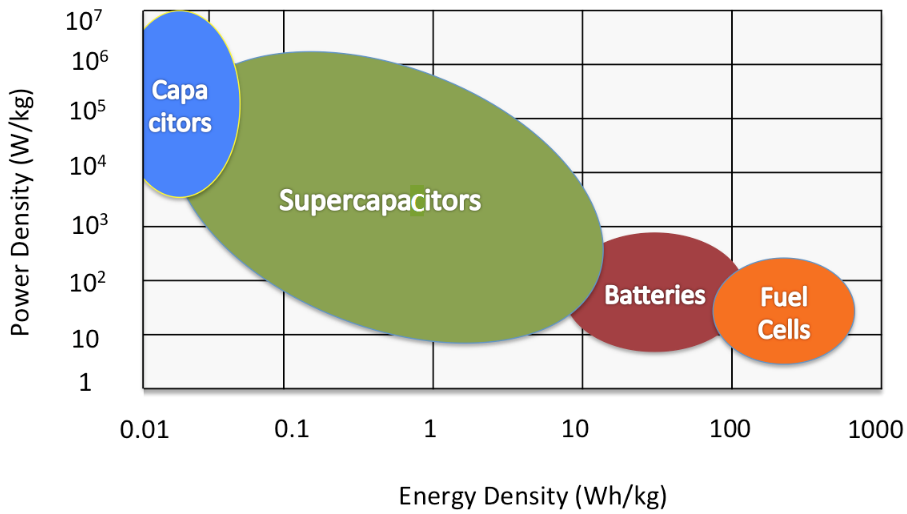
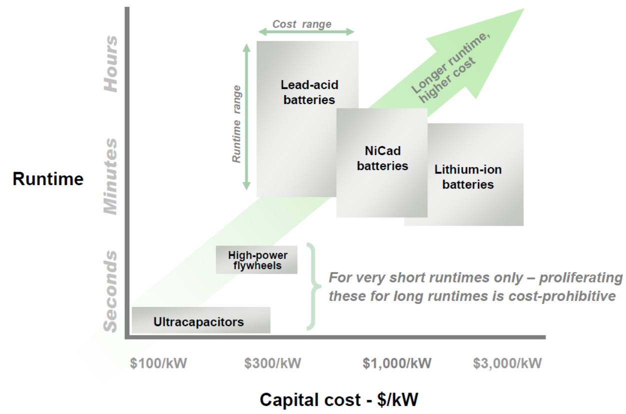


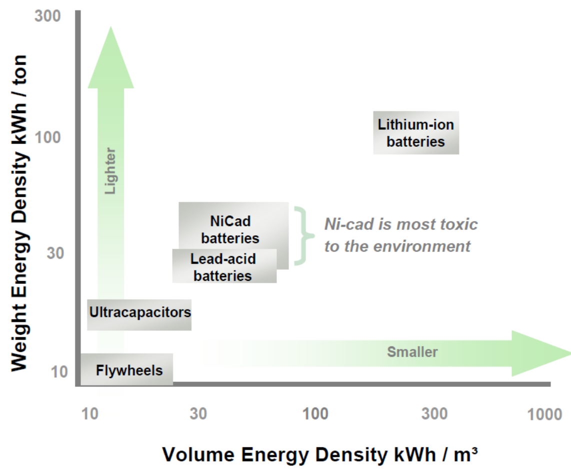
Figure 10.2: Ragone chart showing specific energy versus specific power for capacitors, supercapacitors, batteries, and fuel cells [70].

10.2 Applications

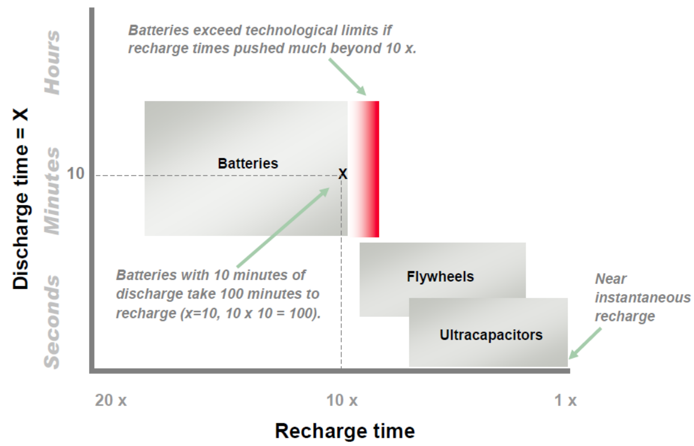
Supercapacitors are primarily used when large amounts of energy need to be repeatedly stored and delivered in bursts. Rapid charging rates and high energy and power densities make them prime candidates for backup power applications and for balancing loads on the grid [70]. For example, the increased deployment of smart meters has demanded backup power for electric and gas meters to avoid system failure. Supercapacitors are ideal for this application because of their ability to turn on immediately and their ability to operate in a wide range of temperatures [72]. Similar to flywheels, they are particularly effective in bridging power gaps lasting from several seconds to several minutes. Power bridging is a critical service that must be installed to ensure consistent power in case of failure or maintenance of a generator or other energy source. Only recently have supercapacitors been considered for large-scale UPS, a service that has been largely dominated by lead-acid batteries. These batteries, however, have short lifetimes (one to five years), require significant maintenance, and are difficult to handle due to toxic components. Lead-acid batteries, for example, require regular inspections, connections verification, and (in some cases) water additions. The comparatively short cycle life of batteries increases the total cost because the storage asset must be replaced more often [88]. Figure 10.3a compares the capital costs of several energy storage technologies. It should be noted, however, that although capital costs is an important index, the graph excludes operating and maintenance costs. It would be more meaningful to examine a graph showing the total cost of ownership, which would significantly shift the batteries further to the right. Another disadvantage of batteries is their size and weight. Data centers, for example, consist of compact rows of racks that contain limited space. Supercapacitor modules can easily fit into standard UPS battery racks [87]. The argument can be made that the use of supercapacitors in large-scale UPS has improved reliability, system availability, and cost of ownership. Their practical applications will be discussed in the following sections.



(a) Runtime vs. captial cost for batteries, supercapacitors, and flywheels [88].



(b) Weight energy density vs. volume energy density [88].



(c) Discharge time vs. recharge time [88].

Figure 10.3: Graphs comparing batteries, supercapacitors, and flywheels.

Data center applications

Energy storage is crucial for data centers' servers and communications devices in the case of interruptions to the main power supply. The most applicable storage technologies for use in data centers are batteries, supercapacitors, and flywheels. Energy storage provides the power needed after a disturbance occurs requiring a rapid switch to an alternative power source. The energy storage technology must be able to provide instant power supply that meets the critical load through the UPS (see figure 10.4) and provide power long enough for the backup supply to come online (i.e. the time it takes for a generator to start up). The loss of data in a data center due to an outage could be incredibly costly, for example, if the data center is supporting a banking transaction worth millions of dollars. The benefit of using batteries as backup sources of energy is their ability to support the critical load of the data center for several minutes to several hours. Common types of batteries for data center applications include flooded lead-acid, valve-regulated lead acid (VRLA), nickel cadmium, and lithium-ion batteries. Lead-acid batteries are most prevalent because of their dominance in two critical categories: cost and performance history. However, lithium-ion is projected to strongly compete in this market in the coming years due to distinct advantages, such as higher power and energy densities than lead-acid batteries (see figure 10.3b) [88].

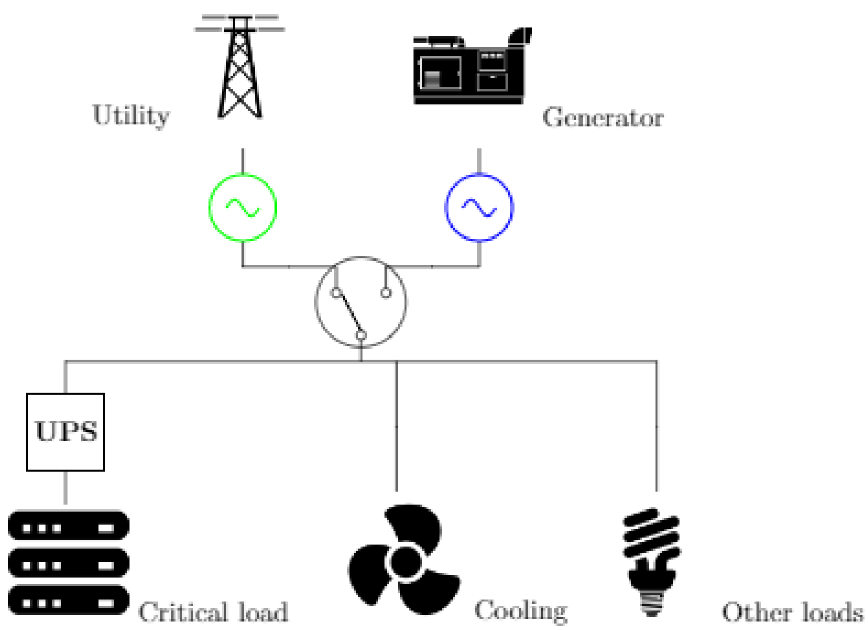


Figure 10.4: A simple diagram showing the power path in a data center context. The UPS consists of either batteries, flywheels, supercapacitors, or a combination of these energy storage technologies. They provide brief, immediate power during the switch to a generator [88].

Flywheels typically are only able to provide power for eight to fifteen seconds at full power. The longer runtime of batteries allows humans and software to perform emergency procedures and safeguard data. As a result, flywheels are often used in conjunction with a standby generator for increased runtime. Flywheels can additionally be used in conjunction with battery-based UPS systems for short-duration power disturbances, leaving batteries only for longer duration power outages. The use of flywheels is especially applicable in conditions where rapid absorption and release of stored energy is vital. Figure 10.3c compares the charge/recharge capabilities of the discussed energy storage technologies. Supercapacitors are viable options for replacing batteries in scenarios where long runtimes are not required. Their ability to go through a large number of charge/dishcharge cycles without degradation is a distinct advantage over batteries. In situations where a high frequency of short-term (less than two minutes) power outages occurs, supercapcitors would be a highly reliable energy storage option with little to no maintenance costs. Although still in the developmental stages, supercapacitors have proven to be effective in power bridging and peak shaving applications, two vital energy storage services [88].

Rengenerative braking applications

Supercapacitors have penetrated the regenerative braking market in electric vehicles and transit systems over recent years [71]. One study shows that using regenerative braking in urban transit systems can reduce energy use by 10 to 45%. Regenerative braking can additionally be used to mitigate voltage drops at the feeder lines or high power peak consumptions. For urban rail applications, the life cycle of the energy storage unit has a profound effect on the final costs of the system. Supercapacitors, flywheels, and superconducting magnetic energy storage (SMES) units can be charged/discharged several hundred thousand times while batteries are capable of significantly fewer cycles. Figure 10.5 compares the capital costs of batteries, flywheels, supercapacitors, and SMES systems. According to Paumanok Publications Inc., transportation applications make up 40% of the USD 400 million global supercapacitor market. The Southeast Pennsylvania Transit Authority (SEPTA) received a grant in 2012 to install a 1 MW wayside storage demonstration project that used supercapacitors to buffer the discharge/recharge cycle of batteries, effectively extending their lifetime. The supercapacitors are also used to improve SEPTA's performance score by making the batteries more available. In order to financially justify an expansion to the wayside project, it would have to save money and generate revenue. To avoid paying high capital costs, SEPTA partnered with the electricity retailer Constellation to aid in the expansion of the demonstration project to commercial scale by adding seven storage devices, totaling 8.75 MW of power. So far, SEPTA has reduced its energy bill by USD 40.000 and generated roughly USD 200.000 in annual revenue from the project [74]. Figure 10.6 shows a schematic diagram of a train in charging mode as it is braking and a train in discharging mode as it is accelerating, using on-board energy storage systems. Energy storage eliminates the need for energy storage between vehicles. When the regenerative energy is exchanged between vehicles, timetables must be optimized to synchronize accelerating and decelerating trains in the same electrical section through the feeder lines. The Rennes metro in France recorded 12% annual savings from optimizing timetables to decrease energy consumption. While energy storage allows for greater flexibility in reusing energy, its implementation is more costly [73].

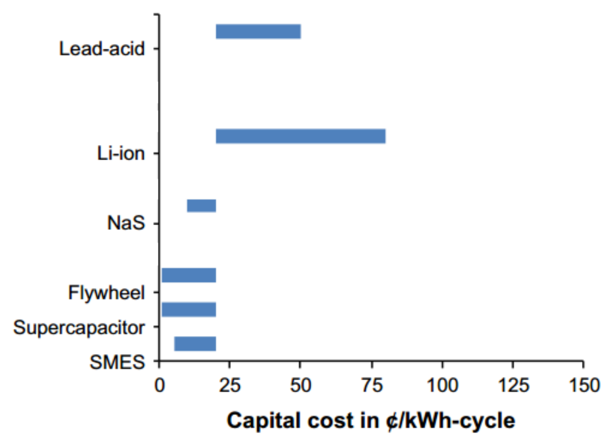


Figure 10.5: Graph showing costs per unit energy for several energy storage technologies [73].

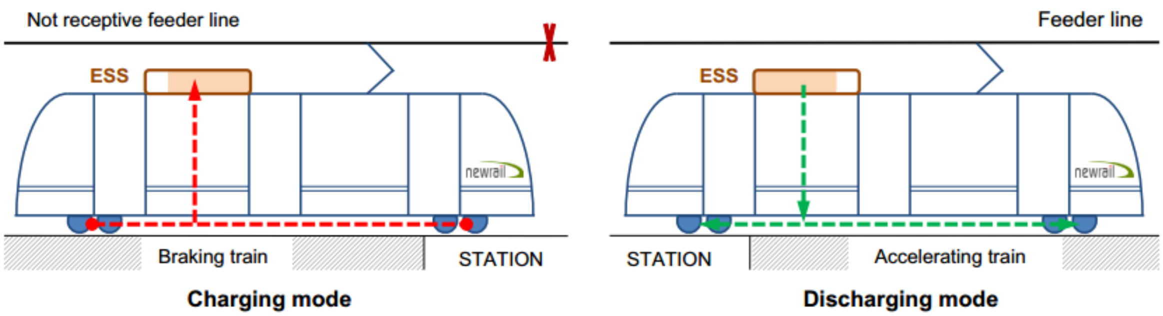


Figure 10.6: Schematic diagram of on-board ESS operation in urban transit system [73].

Chapter 11

Superconducting Magnetic Energy Storage

This technology stores electricity within the magnetic field generated by a current in a superconducting coil and releases the electricity by discharging the coil. When a coil is cooled below its superconducting critical temperature, there is negligible electrical resistance allowing for high efficiency energy storage. SMES is capable of discharging large amounts of power instantaneously. Similar to supercapacitors and flywheels, SMES has negligible performance deterioration due to cycling, however, it has a high self-discharge rate. This technology penetrates similar markets as superconductors and flywheels, such as load leveling and improving voltage stability and power quality to mitigate the negative aspects of RES [80, 81, 82]. A current problem with this technology, however, is the high capital costs associated with cooling units needed to cryogenically cool the coil. Advancements in superconductor technology, such as the increase of the critical temperature of the superconducting transition, have steered recent developments of SMES in the direction of small-scale application [81].

The energy that can be stored in a SMES unit is given by the following equation:

$$E = \frac{1}{2} \cdot L \cdot I^2$$

where L is the inductance of the coil and I is the current in the coil. It can be seen from this equation that the energy can be optimized by manipulating the L and I variables. However, the optimal values of these two variables are constrained by their technical and economic feasibility. By increasing the current I, a stronger, more expensive conductor must be used. On the other hand, increasing the inductance L can be done by increasing the number of turns in the coil. This, too, will require a more expensive conductor. Figure 11.1 shows the main components of a SMES system.

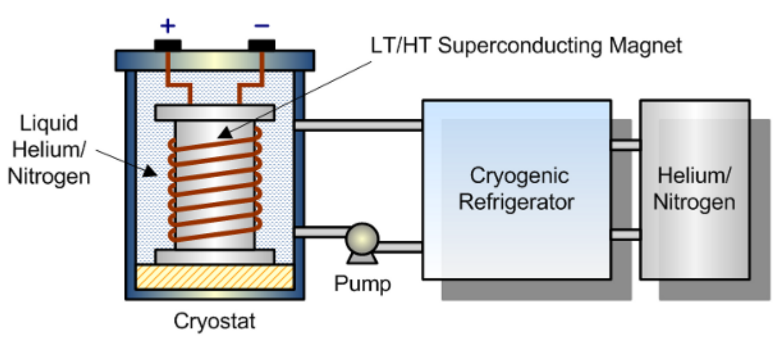


Figure 11.1: Schematic diagram of SMES technology [81].

Chapter 12

Conclusion

The demand for energy storage on today's grid is increasing significantly, as governments around the world require decreased emissions and an increase in intermittent RES. Several energy storage solutions were presented in this report, including those that have yet to be commercialized. These solutions have applications in a wide range of grid-services, such as providing backup power, bulk storage, load leveling, improving power quality, etc. These solution have all shown much potential and earned their spot in the discussion of effective energy storage on the grid.

The wide adoption of EV's in the near future could potentially play a significant role in balancing loads on the grid. With the development of V2G technology, energy could be stored efficiently and cost effectively. Proper government subsidies, along with appropriate regulation to limit CO_2 emissions would encourage the use of EV's and the construction of the necessary infrastructure, including charging stations connected to smart grids. In Iceland, the government has taken initiative by removing the excise and value-added tax on EV's. V2G exploits the energy storage capabilities of our vehicles and allows utility grid operators to communicate with plugged-in cars to either purchase electricity from EV owners during peak loads or to sell electricity during off-peak times when prices are low. The prospect of batteries extends beyond vehicles. Several new technologies, including LMB's, have shown promising results for grid energy storage. However, V2G is unnecessary in Iceland, where there is sufficient hydro power to eliminate the need for energy storage in our EV's.

Costs of utility-scale batteries are expected to reduce significantly in the future, mainly due to technological advances and economies of scale. These lower costs could allow batteries to penetrate the ancillary service market on the grid and be competitive with other energy storage technologies in the near future. Flywheels contrast batteries in the sense that they barely degrade over time and have very quick response times and ramp rates. Both technologies, however, deliver valuable services to the grid, aid in the integration of RES, and reduce the need for peaker plants to supply power during times of high demand. Supercapacitors offer similar services to the grid as flywheels, such as UPS applications, leading to competition between the two technologies. Creating low cost technologies with high performance will be crucial for the mass deployment of flywheels and supercapacitors.

Pumped-storage remains by far the largest and most cost-effective way of storing energy on the grid. This energy storage solution has a high round-trip efficiency and can efficiently stabilize supply on the grid on a minute-to-minute basis [89]. The most significant limitations of the deployment of more pumped-storage facilities are the strict geographical constraints and high capital costs. Nevertheless, companies and governments continue to invest in the construction of new facilities. Energy storage using the gravitational potential energy of solid masses, on the other hand, offers high capacity energy storage with lower capital costs and less geographical dependence than pumped-storage. Although CAES shares the pumped-storage's problem of geographical constraints, it can play a significant role in peak shaving and the integration of RES to the grid. It will be interesting to follow the ADELE adiabatic CAES project to see whether it can act as a competitive energy storage service in the future.

Thermal storage offers another energy storage solution that is capable of large capacity energy storage and not site-dependent. Companies such as Isentropic claim low levelized costs of storage and the ability to compete with pumped-storage at the grid-scale level. The commercialization of more thermal energy storage technologies will be interesting to observe, considering the promising results they have shown through pilot tests on the grid.

Intermittent RES have made it more difficult to match supply with demand, resulting in a market for energy storage on the grid. Many countries are, for example, unable to integrate wind power with hydro as is possible in countries such as Iceland, and as a result must turn to energy storage. Energy storage technologies must buffer the energy from wind and solar energy sources during off-peak hours and provide the necessary grid services at a later point when demand is high. These vital ancillary services, such as spinning-reserves, reserve power, voltage control, etc., provided by energy storage technologies, play an essential role in balancing loads on the grid and ensuring smooth operation. In addition, demand side management using smart grids will play a critical role in shifting demand, allowing both end-users and utilities to decrease costs.

Appendix A

Grid-scale energy storage technologies

The following table gives a brief overview of the costs, area, efficiency, lifetime, and environmental impacts of the energy storage technologies discussed in the report. Figure A.1 shows the worldwide energy storage

Table A.1: Comparison of energy storage technologies discussed in the report.

ES Technology	Space	Round-trip efficiency	Lifetime (y)	Environment
Utility-scale batteries	Small	65-90%	10+	Mild
Pumped-storage	Large	65-85%	40+	Mild
CAES	Large	42-54%	40+	Mild
PHES	Medium	72-80%	20+	Benign
Flywheels	Small	85%	20+	Benign
ARES	Large	78.3%	30-40	Benign
Supercapacitors	Small	95%	20+	Benign

capacity of the primary energy storage technologies up to 2014. Pumped-storage overwhelmingly leads other technologies in terms of installed capacity; however, in recent years, alternative energy storage technologies have grown in popularity. As energy storage companies continue to reduce costs of their products to competitive levels and offer reliable and robust grid services, the deployment of these technologies will increase significantly in coming years.

Figure A.2 compares the power and energy capacities of pumped-storage facilities and alternative energy storage technologies. It is observed that pumped-storage has the largest capacity for both power and energy, in addition to being low-cost for both load leveling and long-term storage applications according to figure A.3. ACAES is effective for load leveling applications, but trails behind pumped-storage in long-term storage applications. The storage cost per cycle for batteries is significantly higher than for pumped-storage, ACAES, and hydrogen. Batteries, however, as shown by figure A.4, possess high round-trip efficiencies as well as having applications in vehicles and electronics, unlike pumped-storage and CAES/ACAES.

In addition to considering storage capacity as a function of power generation, it is interesting to observe area as a function of power generation. This type of graph is shown below in figure A.5, where only area above ground contributes to the area. Figure A.6 shows the same data but uses a logarithmic scale due to the large range of quantities. From the graph, it can be observed that thermal storage takes up significant space compared to other technologies while batteries take up very little space. The area of the CAES plants is arguable misrepresented because they often make use of large, underground reservoirs. It should be

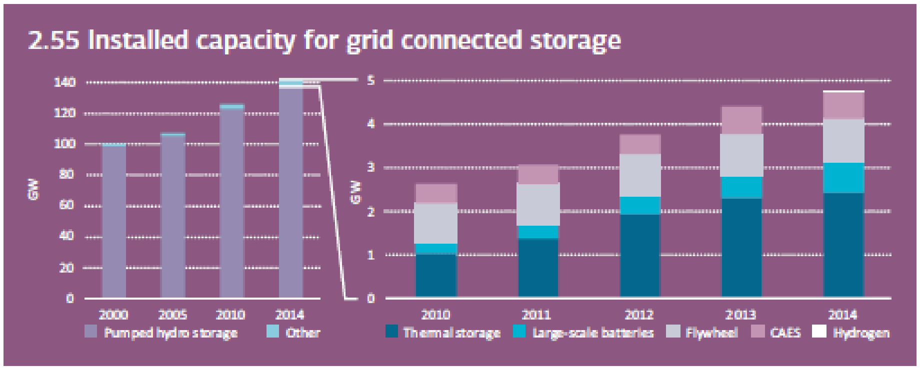


Figure A.1: The installed capacity for grid storage. Although pumped-storage continues to dominate storage capacity, thermal energy, large-scale batteries, flywheels, and CAES are increasing in capacity each year [42].

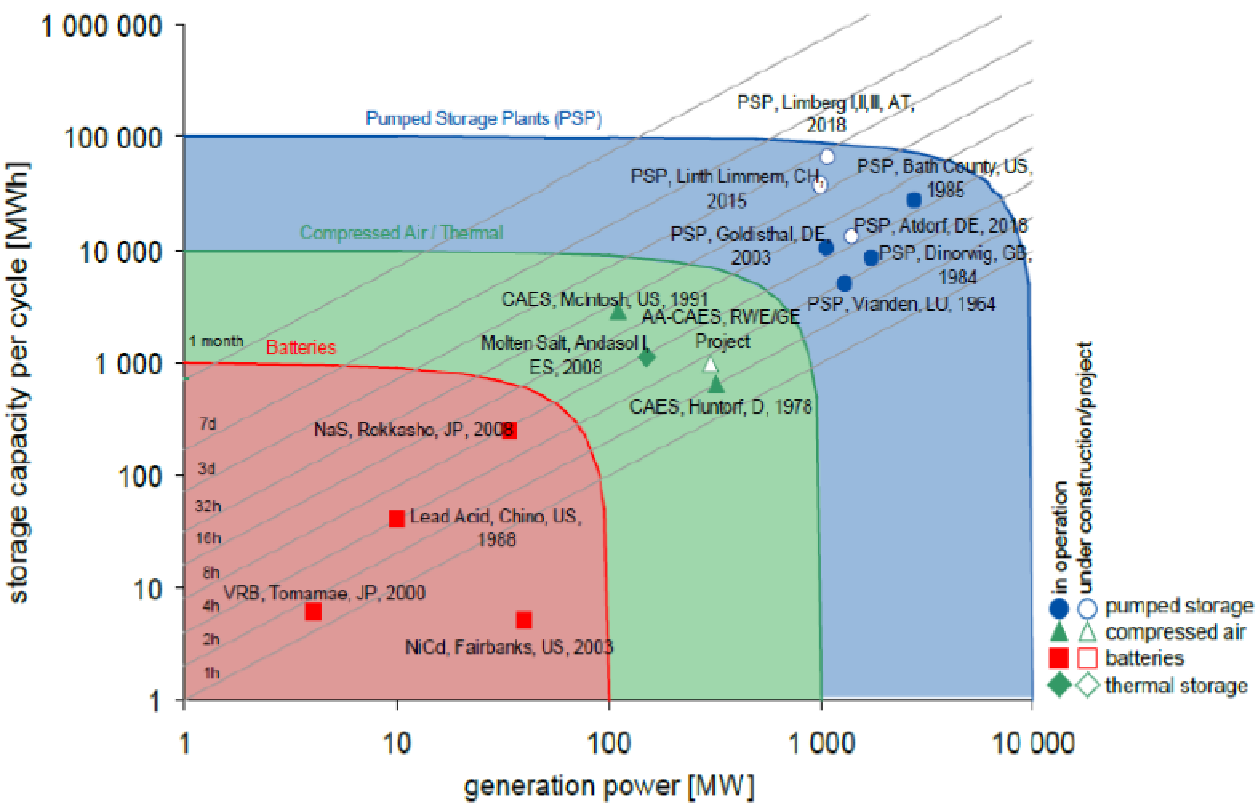


Figure A.2: The graph shows generation power versus energy capacity for batteries, CAES, thermal storage, and pumped-storage. Both operating plants and those in construction are shown [83].

noted the area that is required for pumped-storage facilities is difficult to measure due to rising and falling water levels, as well as the arbitrary measures of a pumped-storage facility's perimeters. As a result, the values obtain in the graph accounted for reservoir area for pumped-storage facilities.

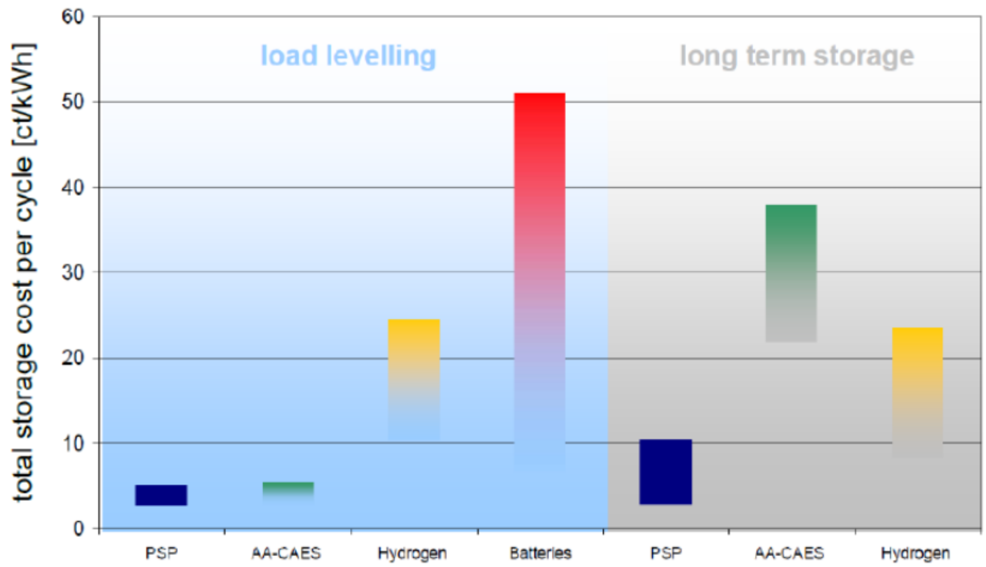


Figure A.3: The graph shows the costs per kWh of several energy storage technologies for load leveling and for long-term storage applications [83].

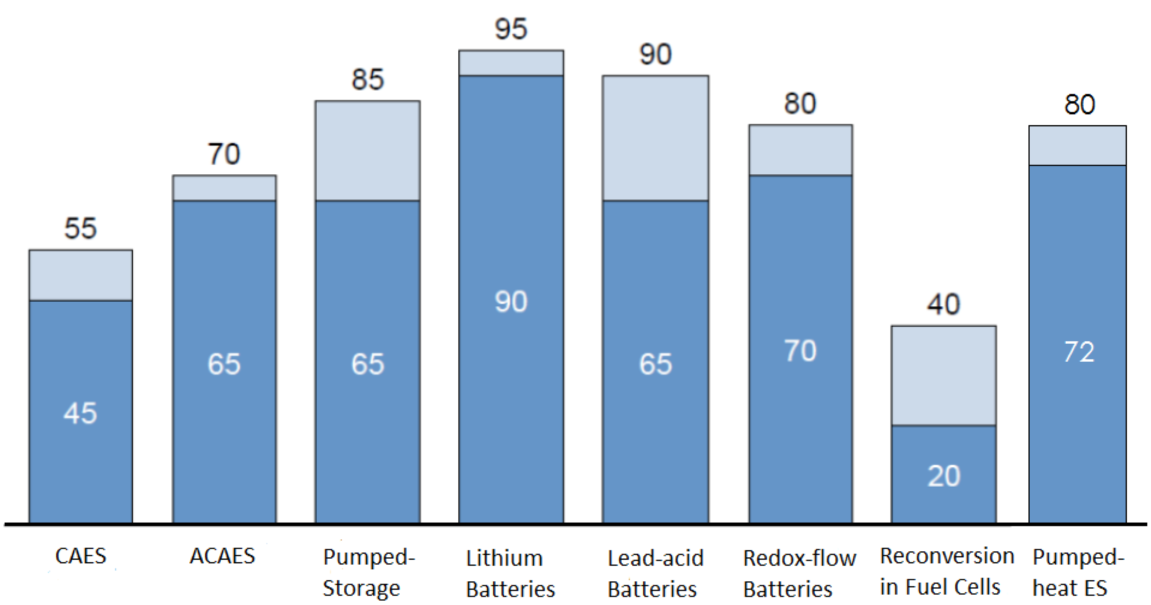


Figure A.4: The graph shows the round-trip efficiencies of several common energy storage technologies [83].

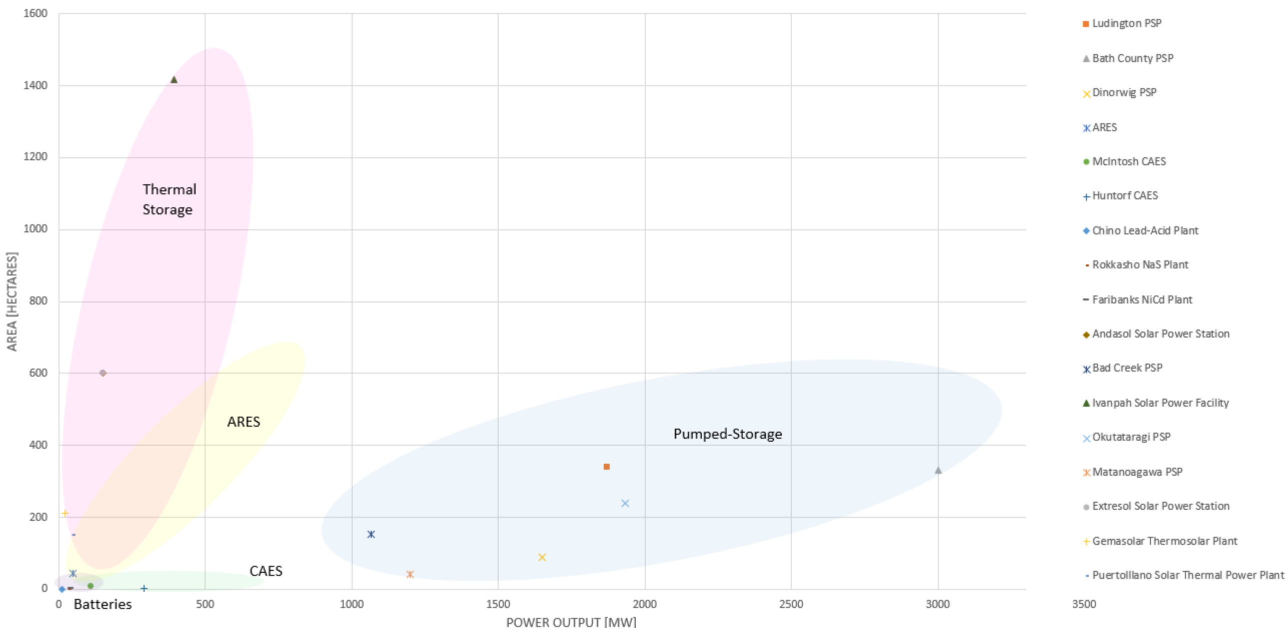


Figure A.5: The graph shows required land area as a function of power generation for several energy storage technologies. Examples of operating plants are shown on the graph.

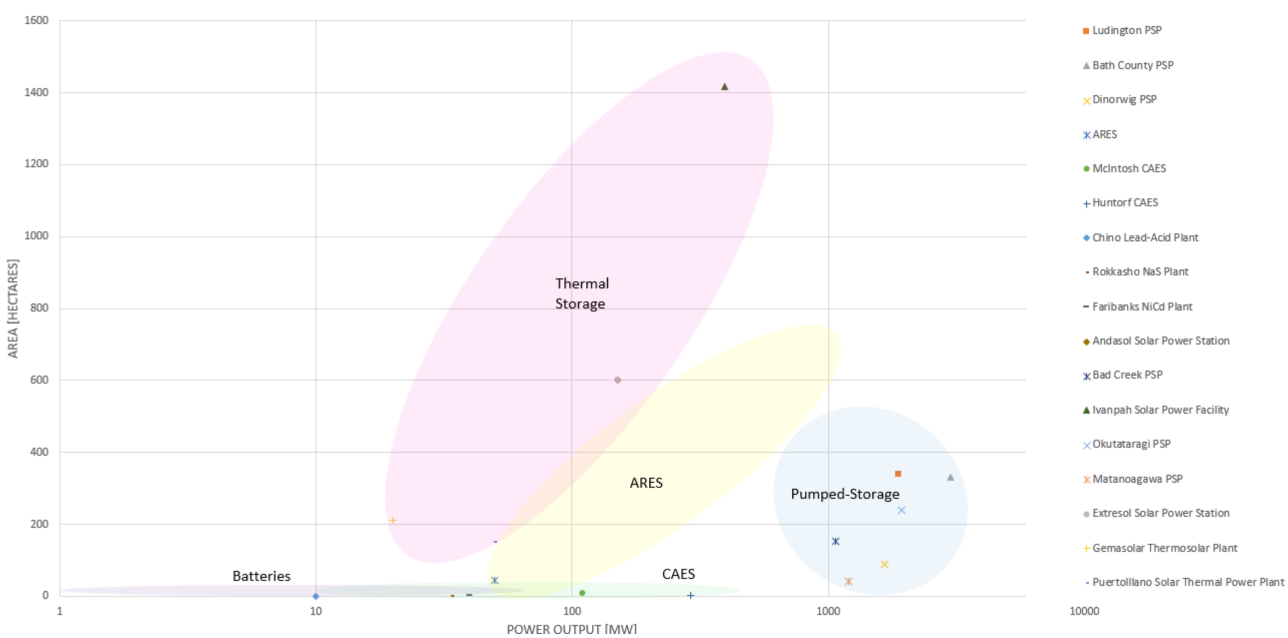


Figure A.6: Required land area as a function of power generation using a logarithmic scale.

Appendix B

Comparison between EV and petrol fueling costs

This section shows the estimated costs of charging electric cars versus fueling petrol vehicles. Throughout the calculations, the electricity price per kilowatt was estimated at $15\frac{ISK}{kWh}$ and the gas price was estimated at $193\frac{ISK}{L}$. The price of electricity was determined by taking the averages of energy prices from electricity vendors and distributors in Iceland using Orkusetur [84]. It was assumed that the company providing the charging station added a five percent markup to the total price. The following tables were used to determined the aforementioned prices:

Energy cost:

Energy vendor	**ISK/kWh**
Fallorka	6,78
HS Orka	6,94
Orka náttúrunnar	6,80
Orkubú Vestfjarða	6,70
Orkusalan	6,99
Rafveita Reyðarfjarðar	6,70
Average cost	**6,82**

Table B.1: Average cost from energy vendors [84].

Energy distributor	**ISK/kWh**
HS þéttbýli	6,67
Norðurorka þéttbýli	6,03
OR þéttbýli	7,55
Orkubú Vestfjarða dreifbýli	9,46
Orkubú Vestfjarða þéttbýli	6,84
Rafveita Reyðarfjarðar þéttbýli	6,56
Rarik dreifbýli	9,73
Rarik þéttbýli	6,46
Average cost	**7,41**

Table B.2: Average cost from energy distributors [84].

Combined average cost [ISK/kWh]	14,23
Markup	5,00%
Final cost at charging station [ISK/kWh]	$14,93 \approx 15,0$

Table B.3: Final cost at charging station per kilowatt-hour.

Petrol cost:
The petrol cost was determined by taking the average of the cost of octane 95 gasoline from four oil companies in Iceland. Electricity and oil prices fluctuate on a daily basis and so there is a sizable margin of error that should be addressed. However, the values obtain in this section give an accurate representation of the prices one would come across today and can easily be adjusted to match changing market conditions.

Gas station	**ISK/L of octane 95**
ÓB	191,4
N1	192,8
Olís	192,8
Skeljungur	194,7
Average cost	$192,9 \approx 193$

Table B.4: Average cost of petrol from four of the largest petrol companies in Iceland [90].

Table B.5 shows the cost per kilometer and cost per charge for four models of EV's, along with their energy capacity, battery type, range, and efficiency. Figures B.1 and B.2 show the cost per kilometer and cost per charge in a graphical format, respectively.

Table B.5: Comparison of four models of EV's.

Model	**Battery (kWh)**	**Battery type**	**Range (km)**	**kWh/km**	**Energy cost ISK/km**	**Cost per charge (ISK)**
BMW i3	22	LMO/NMC	135	0,163	2,44	330
Nissan Leaf	24	Li-manganese	170	0,141	2,12	360
Tesla S	60	NCA	275	0,218	3,27	900
Renault Zoe	22	Li-ion	240	0,0917	1,38	330

The energy consumption per kilometer of the EV's was calculated using the following formula:

$$\alpha = consumption\ per\ kilometer \left[\frac{kWh}{km}\right] = \frac{Energy\ capacity\,[kWh]}{Range\,[km]}$$

In order to calculate the energy cost per kilometer, the energy consumption per kilometer was multiplied with the cost per kilowatt-hour assumed to be $\rho = 15,0\frac{ISK}{kWh}$:

$$\gamma = Cost\ per\ kilometer \left[\frac{ISK}{km}\right] = \frac{Energy\ capacity}{Range}\left[\frac{kWh}{km}\right] \cdot Cost\ per\ kilowatt{-}hour \left[\frac{ISK}{kWh}\right] = \alpha \cdot \rho$$

The cost per charge was subsequently calculated by multiplying γ with the range:

$$v = cost\ per\ charge\,[ISK] = Cost\ per\ kilometer \left[\frac{ISK}{km}\right] \cdot Range\,[km]$$

Table B.6 shows the cost per kilometer of electric and petrol vehicles. As can be seen in the table, electric vehicles have significantly lower costs per kilometer. Low charging prices will most certainly influence customers looking to purchase electric vehicles instead of fossil-fuel dependent ones. The results obtained in this section are promising, however, mass deployment of PEV's will not occur without sufficient infrastructure, such as, a large number of charging stations.

Table B.6: Cost per kilometer for several electric and petrol vehicles.

Type	Car model	Cost per kilometer [ISK/km]
Electric	BMW i3	2,44
	Nissan Leaf	2,12
	Tesla S	3,27
	Renault Zoe	1,38
Petrol	Toyota Yaris	11,58
	BMW 3-series	16,21

Figure B.1 displays the values obtained in table B.6 in a graphical format. The blue columns correspond to electric vehicles while the orange columns correspond to petrol ones. Figure B.2, on the other hand, shows the cost of fully charging each of the four electric vehicles. Although these values do say as much cost per kilometer, they give a sense of how much one should expect to pay at the charging station at the estimated electricity price. The dark orange columns on figure B.1 exclude all taxes other than the value-added tax, which is the only tax incorporated in the cost of electricity for the four electric cars. The light orange columns include all taxes associated with gasoline.

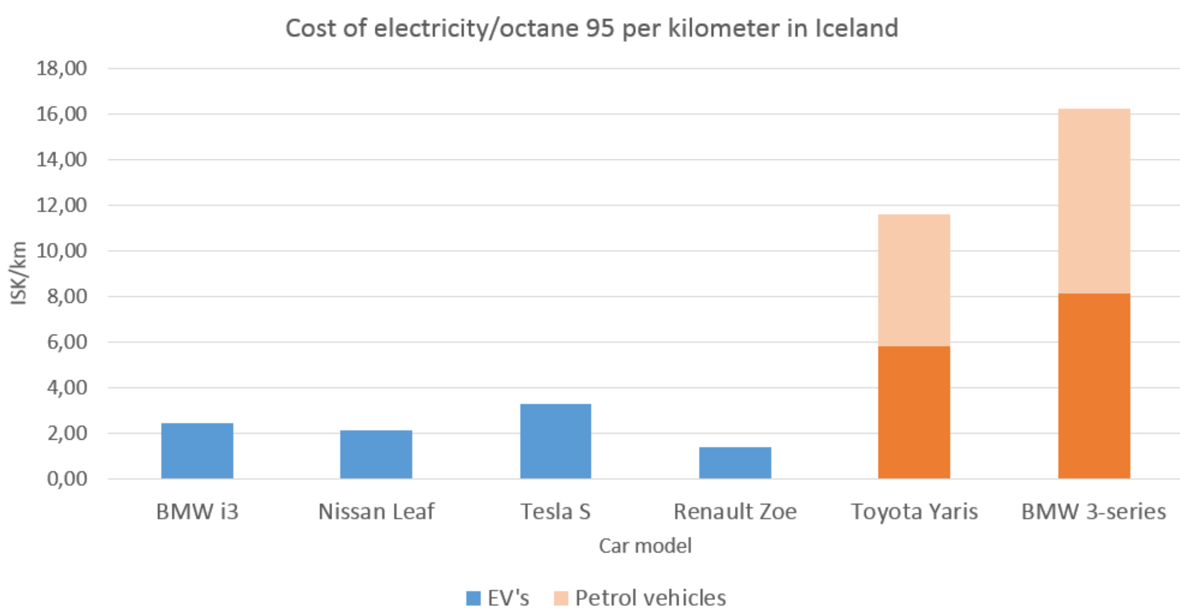


Figure B.1: Cost of energy per kilometer for four models of electric vehicles and two models of petrol vehicles.

The six cars referred to in this section can be seen in figure B.3. The electric cars have a blue border, whereas the petrol ones have an orange border.

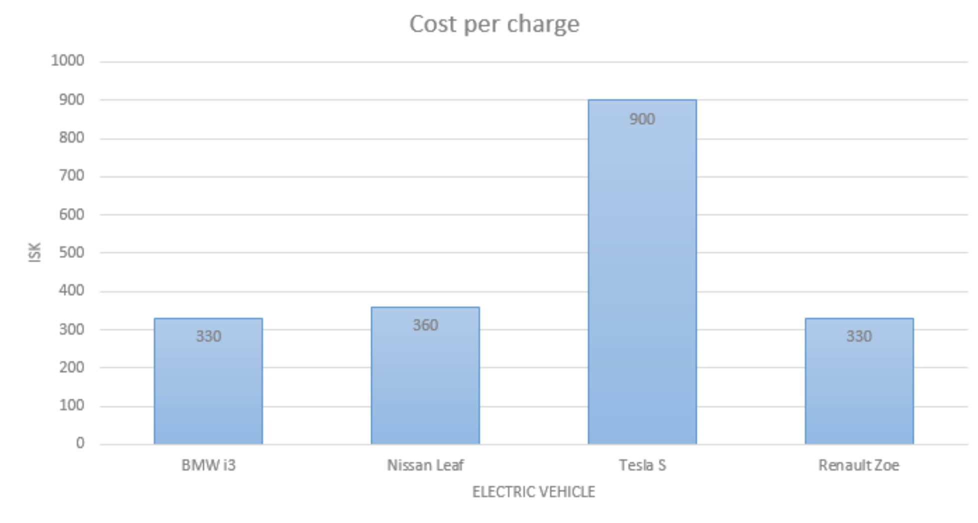


Figure B.2: Cost per charge for four models of electric vehicles.

Figure B.3: Starting from the top left and going right: BMW i3, Nissan Leaf, Toyota Yaris, Tesla Model S, Renault Zoe, BMW 3-series.

Appendix C

Development of energy storage technology

It is important to track the developmental stages of energy storage technologies to observe their progress and maturation, as well as their ability to compete at grid-scale. Some of the more mature utility-scale batteries are generally in the demonstration and deployment stages, and several on the verge of commercialization. Batteries such as aluminum-ion are still at the research and development stage whereas batteries such as LMB's lie somewhere at the demonstration and deployment stage. Energy storage technologies such as ARES that use mature technologies, but have not yet been deployed, can be categorized in the demonstration and deployment stage as well. Interestingly, the incredibly quick assets that have high power outputs, such as flywheels, supercapacitors, and SMES, are all at the research and development stage, however, it is of the author's opinion that both flywheels and supercapacitors should be placed in the demonstration and deployment stage due to recent advancements. Figure C.2 gives perhaps a more accurate representation of the technical maturity of prominent energy storage technologies.

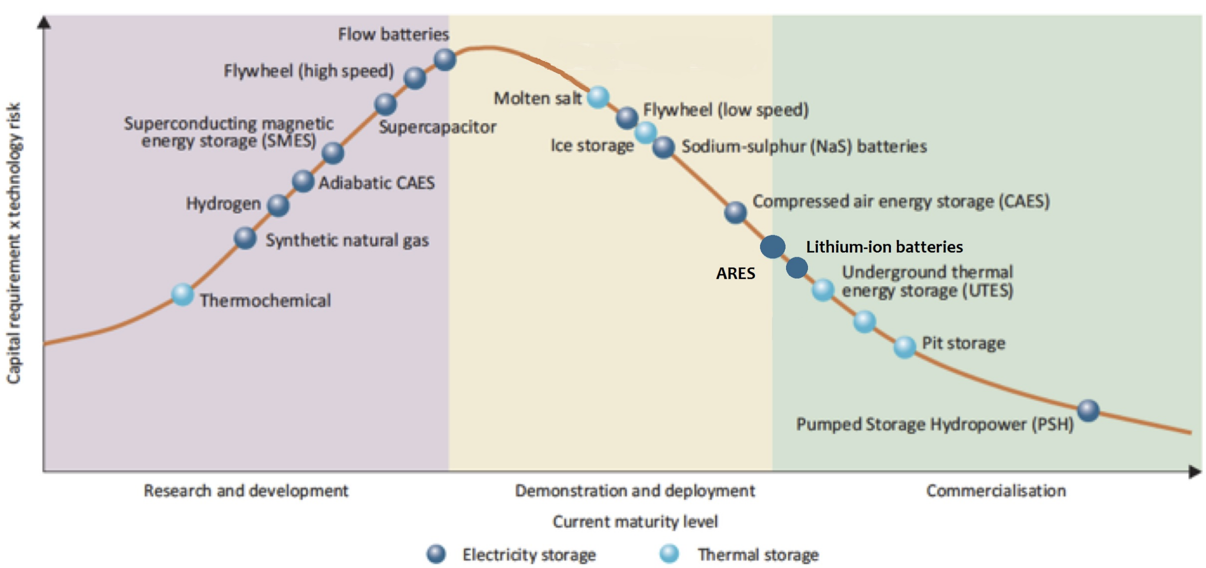


Figure C.1: Graph showing maturity stage versus capital requirement in 2014 [85].

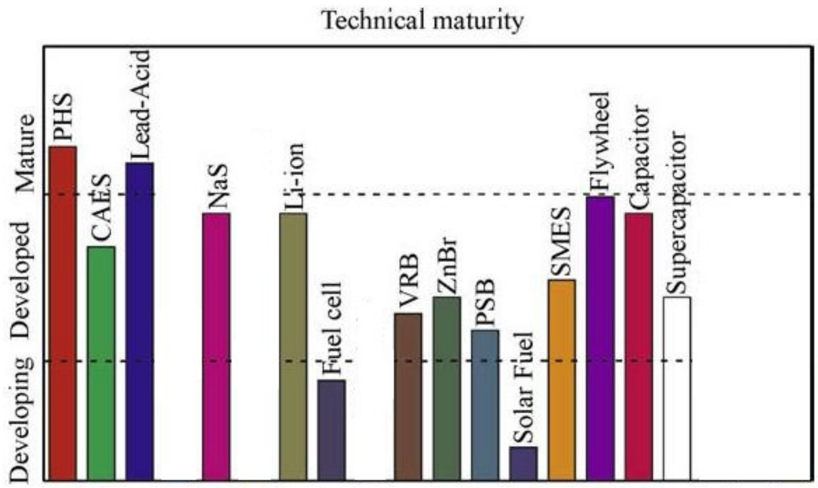


Figure C.2: Comparison of many of the energy storage technologies discussed in the report showing their technical maturity [86].

ACRONYMS

PHS - Pumped-hydro storage
CAES - Compressed air energy storage
NaS - Sodium-sulfur battery
VRB - Vanadium-redox flow battery
ZnBr - Zinc-bromine flow battery
PSB - Polysulfide bromide flow battery
SMES - Superconducting magnetic energy storage

Appendix D

Summary

This section serves as a summary of the energy storage technologies discussed in the report. The intent is to give the reader greater perspective of the applications of these technologies. Figure D.1 displays how the energy storage technologies are categorized, and is followed by table D.1 that shows the main applications of these technologies. Lastly, the suitability of these technologies for performing three primary grid services is displayed in figure D.2. In addition, the power handling capacity and the duration of time that the system can deliver the rated power is shown.

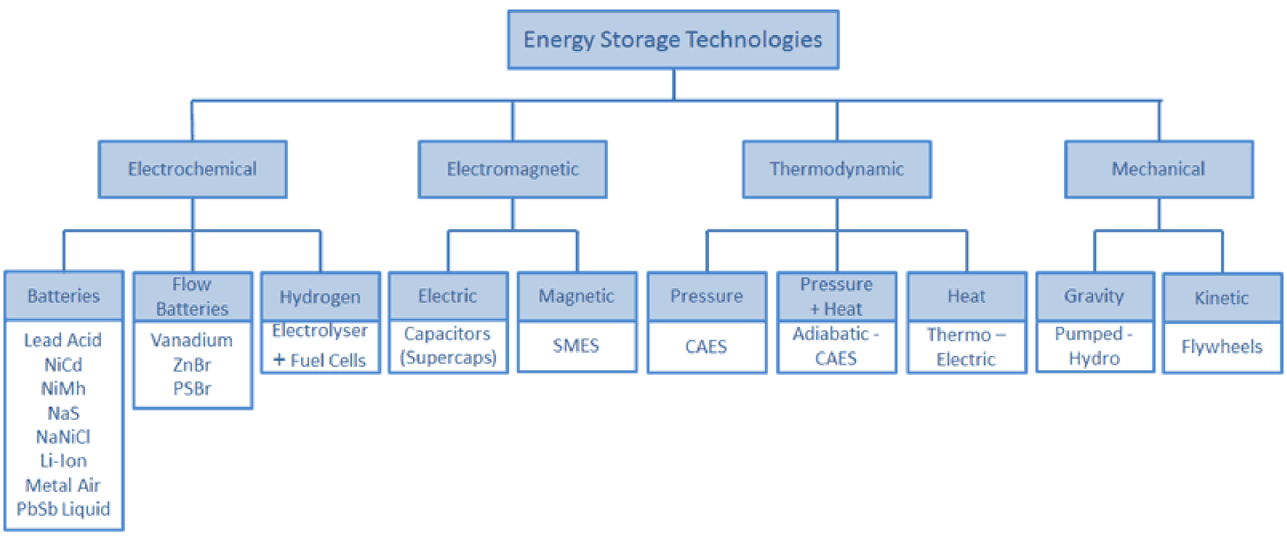


Figure D.1: Categorization of energy storage technologies in chart form [91].

Table D.1: The primary applications of the discussed energy storage technologies [91].

Technology		Primary application
Electrochemical	Advanced lead-acid	Load leveling/regulation Spinning reserve Grid stabilization
	Sodium sulphur	Power quality RES integration
	Aluminum-ion	Ancillary services RES integration
	Lithium-ion	Power quality Frequency reg. Bulk storage EV's
	LMB	Bulk storage
	Flow batteries	Ramping Peak shaving Frequency reg. Power quality Bulk storage
Electromagnetic	Supercapacitors	Power quality Frequency reg. Power bridging Backup power
	SMES	Power quality Frequency reg. Voltage stability
Thermodynamic	CAES/ACAES	Bulk storage Backup and seasonal reserves RES integration
	Pumped-heat ES	Bulk storage
	Liquid-air ES	Bulk storage Power balance
	Hydrogen ES	Ramping Load regulation Contingency reserves EV's
Mechanical	Pumped-hydro	Bulk storage Regulation service Backup and seasonal reserves Energy management
	Flywheels	Load leveling Frequency reg. Peak shaving and off-peak storage Power quality
	ARES	Frequency and voltage reg. RES integration

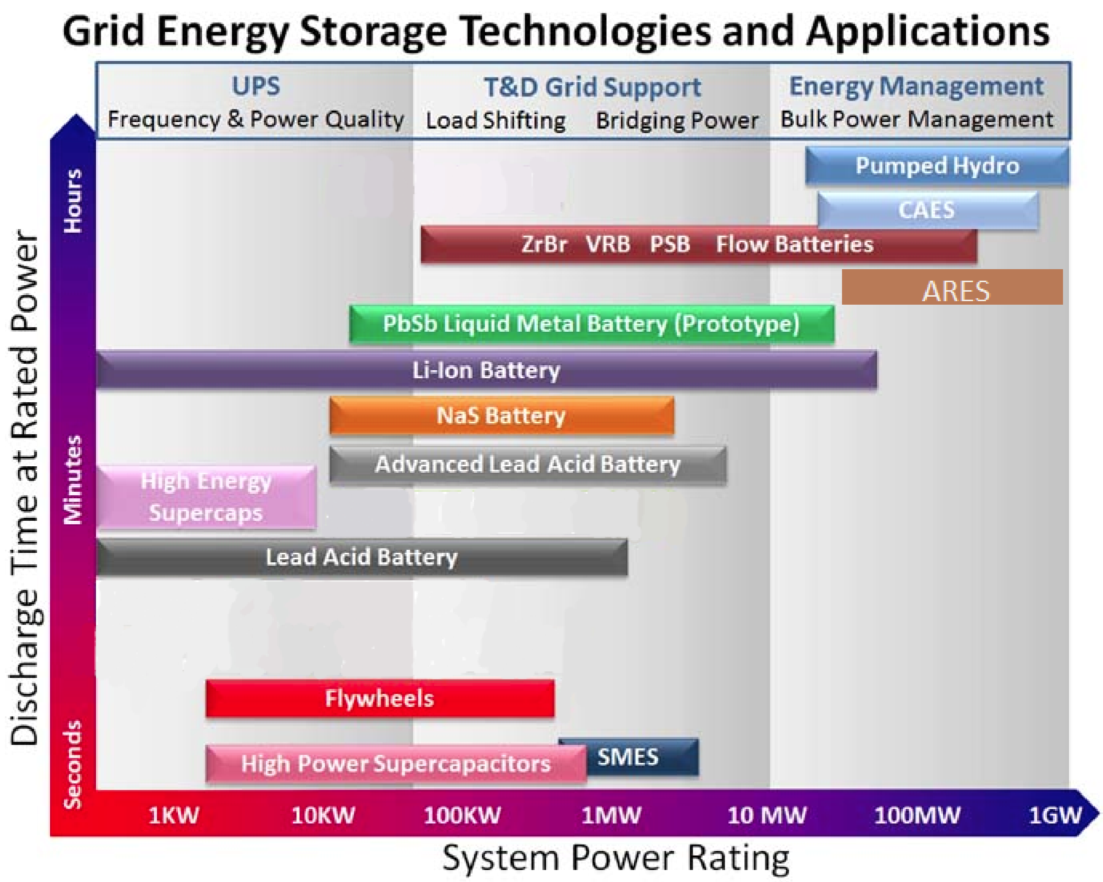


Figure D.2: The graph displays discharge time as a function of power of the energy storage technologies discussed as well as their suitability for performing three critical grid services [91].

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