

Supplementary Information

The future cost of electrical energy storage based on experience rates

O. Schmidt^{1,2*}, A. Hawkes³, A. Gambhir¹ and I. Staffell²

¹Imperial College London, Grantham Institute - Climate Change and the Environment, Exhibition Road, London SW7 2AZ, UK.

²Imperial College London, Centre for Environmental Policy, 14 Princes Gardens, London SW7 1NA, UK.

³Imperial College London, Department of Chemical Engineering, Prince Consort Road, London SW7 2AZ, UK.

*Corresponding Author: o.schmidt15@imperial.ac.uk

Supplementary Note 1. Additional information on experience rate uncertainty.

Uncertainty affecting all data stems from the use of product prices as proxy for production costs. Based on the theory of learning¹, experience curves can only be used as proxy to project future production costs. Any cost projections considering additional cost factors reflected in the product price (e.g. raw material costs, cost of sales) are subject to these additional cost factors remaining unchanged². In practice, however, experience curves are widely used to project future product prices and have proven useful for multiple technologies^{3,4}. An additional uncertainty regarding the use of product prices as proxy for production costs relates to early stage markets, in which these quantities might deviate in particular^{2,5}. Only four out of the eleven datasets cover the recommended two orders of magnitude in data length, i.e. cumulative installed capacity, to avoid this shortcoming⁶.

Experience or learning rates are ideally derived for specific components of industry goods^{2,7}. By reporting prices on pack- or system-level, there is uncertainty due to aggregation of potentially different experience rates of individual components (e.g. cells, housing, power electronics, inverters) and due to inclusion of non-manufacturing related costs (e.g. installation, commissioning), which might follow cost dynamics not captured with experience rates.

Supplementary Note 2. Comment on commodity price uncertainty.

It should be acknowledged that despite using price ranges of the past ten years, there is still high uncertainty on the development of commodity prices. On the one hand, there could be raw material and other input bottlenecks as storage takes off, increasing commodity prices, whilst on the other, the take-off will potentially attract new producers of raw materials and other inputs, depressing commodity prices.

Supplementary Table 1. Overview of product price and cumulative installed capacity data sources, linear regression parameters, indicative C-rates and comments on individual EES dataset.

Pumped hydro – Utility, System	
Price data	2000 – 2015: Average price data for run-of-the-river and pumped hydro plants reported to IEA by OECD member states, South Africa, Brazil and China ^{8–10} . Maximum and minimum values of 2005 – 2010 data excluded ⁹ . 1980 – 2000: Based on mean price and experience rate for large and small hydro ¹¹ . Scaling factor of 0.64 applied to all data points to account for pumped hydro installations only. Factor is based on comparing full 2010 – 2015 dataset with 2010 – 2015 pumped hydro data ¹⁰ . Resulting price range of 270-300 US\$/kWh in line with other findings on pumped hydro costs ^{12,13} .
Capacity data	Capacities and commissioning dates of plants listed in DoE database ¹⁴ .
Model fit	$n_{\text{final}} = 7$; $R^2 = 0.026$; $p = 0.730$; $\sigma = 0.059$ ($N_{2000-2005} = 8$, $N_{2005-2010} = 12$, $N_{2010-2015} = 28$)
C-rate	$C = 1/9.7\text{h}$; Weighted average discharge duration of plants listed in DoE database ¹⁴ , excluding values >100 hours.
Comment	The data is biased towards OECD countries, because majority of data points come from OECD member states. This could be significant since construction of pumped hydro plants is labour-intense.

Lead-acid – Multiple, Module	
Price data	US producer price index for lead-acid batteries larger than BCI dimensional group 8D (Applications: uninterruptable power supply, heavy duty vehicles, etc.) ¹⁵ .
Capacity data	Lead end-use statistics in US, assuming 80% of consumption for battery production ¹⁵ . US data scaled-up to global data based on US share of 30% in global lead end-use ¹⁶ .
Model fit	$n = 21$; $R^2 = 0.105$; $p = 0.153$; $\sigma = 0.042$
C-rate	$C = 1/4.8\text{h}$; Average of $1/3.3\text{h}$ (heavy-duty) ¹⁷ and $1/8\text{h}$ (UPS) ¹⁸
Comment	Data taken from peer-reviewed study ¹⁵ . No economy-wide data on lead-acid battery production or sales available, so US lead consumption is used as proxy ¹⁵ .

Lead-acid – Residential, System	
Price data	Observed prices for systems <30 kWh in German residential market for 2013 - 2016 ¹⁹ .
Capacity data	Based on information from German KfW incentive program ^{20,21} . Scaled to global market assuming German residential storage market is $\sim 1/3$ of global ^{22,23} .
Model fit	$n = 4$; $R^2 = 0.917$; $p = 0.042$; $\sigma = 0.041$
C-rate	$C = 1/3\text{h}$; Average value for residential lead-acid batteries sold in Germany ^{24,25} .
Comment	2016 data represent first half of the year. No data for second half of year recorded, because only 4% of new installations were lead-acid (96% lithium-ion). This is down from $\sim 50\%$ in 2013.

Lithium-ion – Electronics, Battery	
Price data	Japanese Ministry for Economy, Trade and Industry (METI) statistics on Li-ion consumer batteries 1995–2011 ²⁶ .
Capacity data	Annual production data for consumer electronics lithium-ion batteries ^{27,28} .
Model fit	$n = 17$; $R^2 = 0.947$; $p = 6 \times 10^{-11}$; $\sigma = 0.031$
C-rate	$C = 1/2\text{h}$
Comment	-

Lithium-ion – Electric Vehicles, Pack	
Price data	Annual battery pack price index for 2010 - 2015 ²⁹ , 2016 ³⁰ .
Capacity data	Annual figures for EVs sold and respective battery pack size ²⁹ .
Model fit	$n = 7$; $R^2 = 0.903$; $p = 0.001$; $\sigma = 0.037$
C-rate	$C = 4/h$; Average between Tesla S P85D and Nissan Leaf MY 2011/2015
Comment	Experience rate of 16% higher than recently modelled experience rate of 6-9% ³¹ . But, respective study claims that accounting for chemistry advances and economies of scale makes rate of 12-14% conceivable ³¹ .

Lithium-ion – Residential, System	
Price data	Observed prices for systems <30 kWh in German residential market for 2013 - 2016 ¹⁹ .
Capacity data	Based on information from German KfW incentive program ^{20,21} . Scaled to global market assuming that German residential storage market is ~1/3 of global ^{22,23} .
Model fit	$n = 5$; $R^2 = 0.954$; $p = 0.023$; $\sigma = 0.030$
C-rate	$C = 1/3h$; Average value for residential lithium-ion batteries sold in Germany ^{24,25} .
Comment	Becoming dominant technology in German market with market share of 96%, up from ~50% in 2013 ¹⁹ .

Lithium-ion – Utility, System	
Price data	Observed prices for stationary systems for 2010 - 2015 ³² .
Capacity data	Systems listed in the DoE database larger than 100kWh and operational by 2015 ¹⁴ .
Model fit	$n = 6$; $R^2 = 0.924$; $p = 0.002$; $\sigma = 0.026$
C-rate	$C = 1/1.2h$; Weighted average discharge duration of Lithium-ion systems listed in DoE database ¹⁴ .
Comment	-

Nickel-metal hydride – Hybrid Electric Vehicles, Pack	
Price data	Modelled for 1997-2014 with annual car sales data and price projections for annual production levels ³³ . Checked against official company statements on price reductions.
Capacity data	Toyota Prius sales figures ³⁴ and battery specifications ³⁵ . Toyota Prius sales make up ~50% of total global HEV sales ³⁶ .
Model fit	$n = 18$; $R^2 = 0.979$; $p = 7.78 \times 10^{-15}$; $\sigma = 0.006$
C-rate	$C = 15.6/h$; Toyota Prius Generation III battery specification ³⁵ .
Comment	Approach taken from peer-reviewed study ³⁷ . Price data deflated in Japanese Yen and then converted to US\$ ₂₀₁₅ . Price reduction of 75% from 1997 – 2010 in line with official Toyota statement from 2010 ³⁸ .

Sodium-sulphur – Utility, System	
Price data	Industry reports ^{12,39} , news items ^{40,41} and manufacturer interviews ^{42,43} for 2007-2015.
Capacity data	Systems deployed by NGK ^{44,45} .
Model fit	-
C-rate	$C = 1/6h$; System specification by NGK ^{12,43} .
Comment	NGK dominates market for Sodium-sulphur systems ¹⁴ . No experience rate modelled due to very high standard error of underlying data ($\sigma = 0.299$).

Redox-flow – Utility, System	
Price data	Vanadium redox-flow system prices for 2008 - 2015 by two leading manufacturers and an independent demonstration project ⁴⁶ .
Capacity data	Vanadium redox-flow systems listed in DoE database ¹⁴ .
Model fit	$n = 4$; $R^2 = 0.701$; $p = 0.163$; $\sigma = 0.078$
C-rate	$C = 1/3.6h$; Weighted average discharge duration of systems listed in DoE database ¹⁴ .
Comment	-

	Electrolysis – Utility, Pack	Fuel cells – Residential, Pack
Price data	1956-2002: Industry reports and academic publications ⁴⁷ . 2002-2009, 2014: Manufacturer quotes ^{48,49} .	Japanese Enefarm-type systems ⁵⁰ , updated with 2013-2015 figures.
Capacity data	1956-2002: Industry reports and academic publications ⁴⁷ . 2002-2014: Based on US\$100mn market size ⁵¹ , average system price for 2002-2014.	Sales numbers for Japanese Enefarm-type systems ⁵⁰ , updated with figures for 2013 – 2015.
Model fit	$n_{\text{final}} = 6$; $R^2 = 0.879$; $p = 0.006$; $\sigma = 0.052$ ($N_{1956-2002} = 11$, $N_{2002-2009} = 9$, $N_{2014} = 8$)	$n = 12$; $R^2 = 0.965$; $p = 1.4 \times 10^{-8}$; $\sigma = 0.017$
C-rate	$C = 1/10h$ assumed; appears feasible on the basis of average residential electricity consumption of 2900 - 3500 kWh/year and residential fuel cell system size of 1kW ⁵² .	
Comment	Alkaline systems	PEM systems; >95% sold in Japan ^{53,54} .

Solar PV Modules	
Price data	Solar PV module price data ⁴ .
Capacity data	Global cumulative capacity ⁴ .
Model fit	$n = 40$; $R^2 = 0.942$; $p = 4.74 \times 10^{-25}$; $\sigma = 0.015$
Comment	-

PV Inverters	
Price data	Inverter price data ³ .
Capacity data	Global cumulative PV shipments ³ .
Model fit	$n = 24$; $R^2 = 0.966$; $p = 1.33 \times 10^{-17}$; $\sigma = 0.012$
Comment	PV inverters < 20kW _p

Supplementary Table 2. Components of electrical energy storage technologies and indicative cost contributions^{55–57}.

Technology Scope	Indicative contribution	Reported technologies
Cell	19% ⁵⁶	
Electrodes	46% ⁵⁵	- (18650 cell costs for EV packs reported at 145 US\$/kWh ⁵⁸)
Electrolyte	14% ⁵⁵	
Separators	15% ⁵⁵	
Current Collectors	19% ⁵⁵	
Terminals	4% ⁵⁵	
Cell container	2% ⁵⁵	
Battery (consumer electronics)	no data	
Power electronics	no data	Lithium-ion (Electronics)
Housing	no data	
Module	Included in pack	
Thermal conductors	9% ⁵⁵	Lead-acid (Multiple)
Cell group interconnectors	0% ⁵⁵	
State-of-charge regulator	85% ⁵⁵	
Terminals	1% ⁵⁵	
Provision for gas release	2% ⁵⁵	
Module enclosure	3% ⁵⁵	
Pack	11% ⁵⁶	
Wiring harnesses, interconnections and connectors	21% ⁵⁶	Lithium-ion (EV) Nickel-metal hydride (HEV) Electrolysis (Utility) Fuel cells (Residential)
Housing	15% ⁵⁶	
Temperature control	7% ⁵⁶	
Power electronics	24% ⁵⁶	
Battery Management System	33% ⁵⁶	
Ex-works System	35% ⁵⁹	
Inverter	45% ⁹³	-
Container	45% ⁹³	
SCADA/controller	10% ⁹³	
System	35% ⁵⁹	
Transport	-	Lithium-ion (Residential) Lithium-ion (Utility) Lead-acid (Residential) Redox-flow (Utility) Sodium-sulphur (Utility) Pumped hydro (Utility)
Installation	-	
Commissioning	-	
	100%	

Reported price data in this analysis is given for different technology scopes, i.e. cell, battery, module, pack, ex-works system, system. The table above lists the components included within each scope alongside indicative cost contribution for a stationary lithium-ion system. Bold shaded rows give the contribution of each scope to the overall system, and unshaded rows within each block give the contribution of individual components to that scope.

Supplementary Table 3. Commodity price ranges and sources.

Commodity Price Database	US\$/kg	US\$/kg	US\$/kg		
Commodity	Average	Max	Min	Comment	Source
ABS (Acrylnitril-butadienestyrene)	2.00	2.00	2.00		www.roytech.co.uk/Useful_Tables/Matter/Costs_Plastics.html
Activated Carbon	1.65	1.65	1.65	1997	Mercury Study Report to Progress. United States Environment Protection Agency. December 1997
Alpha-alumina	15.60	15.60	15.60		www.inframat.com/products/26R-0806UPA.htm
Aluminium	2.04	2.80	1.51		Bloomberg ⁶⁰
Ammonium Salts in Acetonitrile	1.00	1.00	1.00	assumption	
Antimony	8.04	12.79	4.10		Bloomberg ⁶⁰
Aramid fibres	25.00	25.00	25.00		www.netcomposites.com/guide-tools/guide/reinforcements/aramid-fibrefiber/
Barium	8.33	8.33	8.33		www.ebiochem.com/product/barium-chromate-ar-9980
Beta-alumina (boehmite)	3.07	3.07	3.07	2003	www.gunnarmusan.de/Material/ZEBRA%20Battery%20-%20Material%20Cost,%20Availability%20and%20Recycling.pdf
Binder PVDF	10.00	10.00	10.00		BatPac (Cost Input) ⁵⁵
Brass	8.67	9.16	8.43		Bloomberg ⁶⁰
Cadmium	2.72	7.50	0.94		Bloomberg
Carbon	6.80	6.80	6.80		BatPac (Cost Input) ⁵⁵
Carbon Black	6.80	6.80	6.80		BatPac (Cost Input) ⁵⁵
Carbon Steel	0.72	0.83	0.49		Bloomberg ⁶⁰
Carbon, graphite	10.90	10.90	10.90	Mix Carbon, Graphite	
Cement	0.10	0.11	0.09		Bloomberg ⁶⁰
Cerium Metal	11.80	34.13	4.60		Bloomberg ⁶⁰
Chromium	9.25	13.50	6.35		Bloomberg ⁶⁰
Cobalt	29.21	38.13	24.05		Bloomberg ⁶⁰
Concrete	0.05	0.05	0.05		ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/props.pdf
Copper	6.52	9.60	3.07		Bloomberg ⁶⁰
Ethylene Carbonate	1.06	1.06	1.06		www.ihs.com/products/chemical-technology-pep-reviews-ethylene-carbonate-from-ethylene-2003.html
Ethylene Glycol Dimethyl Ether	5.00	5.00	5.00		www.alibaba.com/showroom/dimethyl-ether-prices.html
Glass	0.19	0.21	0.17		Bloomberg ⁶⁰
Glycol	1.16	1.65	0.87		Bloomberg ⁶⁰
Graphite	15.00	15.00	15.00		BatPac (Cost Input) ⁵⁵
Gravel	0.01	0.01	0.01		Bloomberg ⁶⁰
Halide salts	0.77	0.77	0.77		www.gunnarmusan.de/Material/ZEBRA%20Battery%20-%20Material%20Cost,%20Availability%20and%20Recycling.pdf
High alloy steel	2.25	2.97	1.35	see stainless steel	
Iron	0.72	0.83	0.49	see carbon steel	
Lead	2.03	2.55	1.00		Bloomberg ⁶⁰
Lead oxides	2.03	2.55	1.00	see lead	
Lithium carbonate	5.48	7.00	3.97		minerals.usgs.gov/minerals/pubs/commodity/lithium/myb1-2013-lithi.pdf , Berenberg Bank Report
Lithium hexa-fluorophosphate	13.49	13.49	13.49		BatPac (Cost Input) ⁵⁵
Lithium hydroxide	6.70	6.70	6.70		minerals.usgs.gov/minerals/pubs/commodity/lithium/myb1-2013-lithi.pdf
Lithium manganese oxide	10.00	10.00	10.00		BatPac (Cost Input) ⁵⁵
M: Ni, Ti, V, Zr	13.29	22.72	6.58	Average Price	
Magnesium	2.81	4.30	2.00		Bloomberg ⁶⁰

Manganese	2.37	3.23	1.60		Bloomberg ⁶⁰
Molybdenum	37.91	75.20	13.30		Bloomberg ⁶⁰
Nafion	176.00	176.00	176.00		www.nrel.gov/docs/fy09osti/45457.pdf
Nickel	18.05	33.33	8.82		Bloomberg ⁶⁰
Nickel Compounds	14.44	26.66	7.06	80% Ni content	
Nickel hydroxide	6.00	6.00	6.00		www.arb.ca.gov/msprog/zevprog/2003rule/03board/andermanreport.pdf
PEEK	68.33	68.33	68.33		www.roymech.co.uk/Useful_Tables/Matter/Costs/Plastics.html
PEEK, Aluminium, Copper	25.63	26.91	24.30	Average Price	
Plastics	1.33	1.64	1.00	Average Price	
Platinum	46,018.67	62,434.96	31,448.53		Bloomberg ⁶⁰
Polybenzimidazol (PBI)	195.00	195.00	195.00		cordis.europa.eu/result/rcn/56073_de.html
Polyester	1.50	1.50	1.50		Matteson ¹⁵
Polyethylene	1.60	1.96	1.22		Bloomberg ⁶⁰
Polyethyleneterephthalate	1.35	1.75	1.00		Bloomberg ⁶⁰
Polypropylene	1.40	1.65	1.04		Bloomberg ⁶⁰
Polytetrafluoroethylene	13.56	13.56	13.56	US\$ 4bn market for 295 kT	https://globenewswire.com
Polyvinylchloride	0.99	1.19	0.75		Bloomberg ⁶⁰
Potassium hydroxide	0.50	0.50	0.50		www.alibaba.com/showroom/potassium-hydroxide-price.html
Ruthenium	5,977	21,517	1,481		Bloomberg ⁶⁰
Sand	0.01	0.01	0.01		Bloomberg ⁶⁰
Sb, Sn, As	10.00	10.00	10.00		Matteson ¹⁵
Silica	8.80	8.80	8.80		Lucas, G. Handbook of Composites. Van Nostrand Reinhold Company.
Silicon	1.94	2.29	1.22		Bloomberg ⁶⁰
Silicon Carbide	36.00	36.00	36.00	1999	http://ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/props.pdf
Sodium	0.45	0.65	0.31		Bloomberg ⁶⁰
Stainless Steel	2.25	2.97	1.35		Bloomberg ⁶⁰
Steel	0.72	1.06	0.52		Bloomberg ⁶⁰
Steel and copper	3.62	5.33	1.80	Average Price	
Sulphur	0.11	0.14	0.08		Bloomberg ⁶⁰
Sulphuric Acid	0.11	0.31	0.05		Bloomberg ⁶⁰
Thermal insulation	12.50	12.50	12.50		www.gunnarmusan.de/Material/ZEBRA%20Battery%20-%20Material%20Cost,%20Availability%20and%20Recycling.pdf
Tin	18.16	26.90	10.70		Bloomberg ⁶⁰
Titanium	6.54	15.05	3.20		Bloomberg ⁶⁰
Vanadium	27.38	40.00	13.60		Bloomberg ⁶⁰
Vanadium pentoxide	12.62	16.60	5.25		Bloomberg ⁶⁰
Water	-	-	-		
Wood	0.24	0.25	0.24		Bloomberg ⁶⁰
YBCO	1,333	1,333	1,333		High Temperature Superconductors (HTS) for energy applications, Ziad Melhem, 2011, Woodhead Publishing.
Yttrium	45.78	70.00	34.00		Bloomberg ⁶⁰
Zinc	2.26	4.23	1.21		Bloomberg ⁶⁰
Zirconium	1.18	2.50	0.70		Bloomberg ⁶⁰

Supplementary Table 4. Breakdown of raw material cost contributions for each EES technology.

Supercapacitor⁶¹	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
Ammonium Salts	83	94	104
Aluminium	53	109	202
Activated Carbon	71	77	83
Plastics	4	8	15
Total	211	288	404

Nickel-Cadmium^{61,62}	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
Nickel Compounds	41	164	451
Cobalt	5	13	25
Cadmium	4	21	84
Copper	2	8	18
Chromium	2	6	13
Lithium Hydroxide	1	1	2
Carbon Steel	1	2	3
Plastics	0	1	2
Potassium hydroxide	0	1	1
Nickel	-	-	-
Lithium	-	-	-
Total	56	216	599

SMES⁶¹	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
Copper	42	89	131
Carbon Steel	56	83	95
Yttrium	9	12	18
Barium	6	6	6
Copper	2	4	5
Sulphuric Acid	0	0	0
Total	115	194	256

Flywheels⁶¹	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
Carbon	44	44	44
Carbon Steel	21	31	36
Copper	11	23	35
Plastics	7	14	24
Yttrium	0	2	6
Barium	1	1	2
Copper	0	1	2
Total	84	113	138

Nickel-metal hydride^{61,62}	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
Nickel Compounds	21	83	230
Cerium Metal	4	18	79
Carbon Steel	2	6	10
Plastics	1	0	0
Potassium Hydroxide	0	0	0
Total	27	109	320

PEM fuel cell⁶³	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
Platinum	53	78	106
Graphite	5	6	8
Nafion	1	1	1
Polytetrafluoroeth.	0	0	0
Carbon	0	0	0
Plastics	0	0	0
Copper	0	0	0
Iron	0	0	0
Steel	0	0	0
Plastics	0	0	0
Total	60	87	116

Vanadium redox-flow ⁶¹		US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>	
Vanadium	22	61	112	
Carbon Steel	1	3	4	
Copper	1	2	4	
Plastics	1	2	3	
Graphite	1	2	3	
Carbon Black	1	1	2	
Sulphuric Acid	0	1	4	
Total	28	72	132	

Lithium-ion (LMO) ⁶⁴		US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>	
Lithium mang. ox.	25	25	25	
Carbon, graphite	12	12	12	
Copper	3	5	8	
Aluminium	2	3	4	
Binder PVDF	2	2	2	
Lithium hexafluoroph.	1	2	2	
Dimethyl carbonate	1	1	1	
Ethylene carbonate	0	0	0	
Copper	0	1	1	
Thermal insulation	0	0	0	
Stainless Steel	0	0	0	
Polypropylene	0	0	0	
Polyethyleneterepht.	0	0	0	
Glycol	0	0	0	
Polyethylene	0	0	0	
Total	47	52	56	

Lead-acid ^{61,62}		US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>	
Lead oxides	7	25	45	
Lead	5	18	32	
Plastics	2	5	8	
Antimony	1	3	6	
Sulphuric Acid	0	0	2	
Copper	0	1	1	
Glass	0	0	0	
Total	15	51	95	

ZEBRA ⁶⁵		US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>	
Nickel	13	27	50	
Thermal insulation	4	4	4	
Beta-alumina	4	4	4	
Stainless Steel	1	2	3	
Halide salts	2	2	2	
Copper	1	2	3	
Iron	1	1	1	
Steel	0	0	0	
Total	27	43	67	

Pumped Hydro ⁶¹		US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>	
Concrete	11	16	22	
Iron	1	2	2	
Wood	0	1	1	
Chromium	0	0	0	
Molybdenum	0	0	1	
Plastics	0	0	0	
Aluminium	0	0	0	
Copper	0	0	0	
Zinc	0	0	0	
Lead	0	0	0	
Manganese	0	0	0	
Magnesium	0	0	0	
Total	21	28	34	

Sodium-sulfur ^{61,62}		US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>	
Alpha-alumina	3	3	3	
Aluminium	3	4	6	
Beta-alumina	3	3	3	
Stainless steel	2	3	3	
Copper	1	2	3	
Sodium	0	0	0	
Sulfur	0	0	0	
Glass	0	0	0	
Sand	0	0	0	
Total	12	15	19	

Alkaline electrolyzer⁶⁶	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
Polybenzimidazol (PBI)	5	5	5
Stainless Steel	3	4	6
Nickel	2	4	8
Copper	0	0	0
Graphite	0	0	0
Potassium hydroxide	0	0	0
Aramid fibres	0	0	0
Polytetrafluoroeth.	0	0	0
Aluminium	0	0	0
Iron	0	0	0
ABS	0	0	0
Total	10	14	19

Compressed Air⁶¹	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
High Alloy Steel	0	3	6
Concrete	0	1	2
Carbon Steel	0	0	0
Iron	0	0	0
Manganese	0	0	0
Copper	0	0	0
Plastics	0	0	0
Vanadium	0	0	0
Silicon	0	0	0
Molybdenum	0	0	0
Chromium	0	0	0
Total	1	4	9

H2 pressure tank^{67,68}	US\$/kWh		
<i>Material</i>	<i>min</i>	<i>mid</i>	<i>max</i>
Stainless Steel, Steel, Concrete Vessel	4		
Steel/Concrete Composite Vessel		12	
Stainless Steel			25

Supplementary Table 5. Impact of experience rate uncertainty, based on 95% standard error confidence interval, on cost projections for 1 TWh cumulative installed capacity.

Technology	Central rate		Low rate		High rate	
	ER (central)	Price (US\$/kWh)	ER (low)	Price (US\$/kWh)	ER (high)	Price (US\$/kWh)
Pumped hydro (Utility, System)	-1%	282	-10%	272	6%	293
Lead-acid (Multiple, Module)	4%	166	-1%	136	10%	201
Lead-acid (Residential, System)	13%	294	8%	572	17%	154
Lithium-ion (Electronics, Battery)	30%	137	27%	154	33%	122
Lithium-ion (EV, Pack)	16%	154	12%	191	20%	124
Lithium-ion (Residential, System)	12%	411	9%	643	16%	267
Lithium-ion (Utility, System)	12%	357	9%	521	15%	244
Nickel-metal hydride (HEV, Pack)	11%	198	10%	208	12%	189
Redox-flow (Utility, System)	11%	288	1%	1,132	20%	73
Electrolysis (Utility, Pack)	18%	102	12%	121	23%	87
Fuel cells (Residential, Pack)	18%	223	16%	282	20%	177

Central rate numbers refer to the experience curve based price projections in Figure 2. *Low rate* and *High rate* numbers are based on the lowest and highest experience rate of the 95% standard error confidence intervals respectively.

Cumulative installed nominal energy capacity for pumped hydro (system) and lead-acid (module) is already above 1 TWh. Therefore, projected prices at 1 TWh refer to historic capital costs (pumped hydro: 2000, lead-acid: pre-1989). The price range is then a result of back-casting 2015 prices at different experience rates.

Supplementary Table 6. Comparison of experience curve based cost projections to the literature.

Technology	2030 (\$/kWh)	2040 (\$/kWh)	Literature (\$/kWh)	Method/Comment
Pumped Hydro (Utility, System)	285	287	140 - 230	Long-term estimate for 90% renewables system ⁶⁹
Lead-acid (Multiple, Module)	143	142	194 - 245 120 - 170	Bottom-up engineering model for 'Future State Price' ⁷⁰ Long-term estimate for 90% renewables system ⁶⁹
Lead-acid (Residential, System)	376	284	194 - 245	Bottom-up engineering model for 'Future State Price' ⁷⁰
Lithium-Ion (Electronics, Battery)	129	99	100 100	Experience curve analysis for 2020 ⁷¹ GM forecast for 2022 for pack-grade cells ⁵⁸
Lithium-Ion (EV battery, Pack)	117	72	160 - 300 215* 200 - 300* 200 - 750 200 73	Literature Review for 2030 ³¹ ; Bottom-up Engineering Model for 2030 ⁵⁶ ; Literature Review for 2030 ³⁷ ; Expert Elicitation for 2030 ⁷² ; Forecast for 2020 ⁷³ Experience curve analysis for 2030 ³⁰
Lithium-Ion (Residential, System)	524	397	241 - 318 250 - 620 450 - 550	Bottom-up engineering model for 'Future State Price' ⁷⁰ Analyst projections for 2030 ⁷⁴ ; Experience Curve Analysis for 2030 ⁷⁴ ;
Lithium-Ion (Utility, System)	461	354	241 - 318 250 - 620 450 - 550	Bottom-up engineering model for 'Future State Price' ⁷⁰ Analyst projections for 2030 ⁷⁴ ; Experience Curve Analysis for 2030 ⁷⁴ ;
NiMH (HEV, Pack)	254	211	-	
Redox-flow (Utility, System)	366	286	148 - 259 180 - 250	Bottom-up engineering model for 'Future State Price' ⁷⁰ Bottom-up engineering model for 2GWh demand p.a. ⁷⁵
Electrolysis (Utility, Pack)	130	97	49 - 105	Expert Elicitation for 2030 ⁷⁶
Fuel Cell (Residential, Pack)	320	212	476 - 532	Consultancy report for mass-market production ⁷⁷ (> 10,000 units cum production per company)

*included in above figure

Projections from the experience curves are given in the *2030* and *2040* columns (central ER) and can be compared to the findings from the literature given in the *Literature* and *Method/Comment* columns.

Supplementary Table 7. Parameters and references used for levelised cost analyses.

	ICEV – Fuel tank	EV – Li-ion battery pack	Installed residential Li-ion system
Capital cost	US\$ 180 ⁷⁸	US\$ 9,900 (2016) [*]	1,883 US\$/kWh (2016)
Capacity (distance)	17 gallons (510 mi) ⁷⁹	30 kWh (107 mi) ⁸⁰	-
Experience rate	0% ⁸¹	16% ± 4%	12% ± 4%
Growth Rate^{**}	-	0.348 (0.306, 0.436)	0.500 (0.466, 0.656)
Residual Value	0% (of capital cost) ⁸²	30% ⁸³ (of capital cost)	0% (of capital cost) ⁸⁴
Warranted lifetime	100,000 miles/ 8 years	100,000 miles/ 8 years ⁸⁰	2,500 cycles/ 10 years ⁸⁴
Fuel Price	2.36 US\$/gallon ⁸⁵	0.12 US\$/kWh ⁸⁶	LCOE of residential solar PV ^{****}
Round-trip efficiency	100%	90% ⁸⁷	92% ⁸⁴
Depth-of-discharge	100%	80% ⁸⁷	80% ⁸⁸
Fuel efficiency	30 miles/gallon ⁷⁹	4.46 miles/kWh ^{***}	-
Annual degradation	0% (of capacity)	5% ⁸⁹ (of capacity)	0.5% (of capacity) ⁹⁰
Discount rate	5%	5%	5%
C-rate (1/h)	-	3 C ⁸⁰	0.33 C ^{24,25}
O&M cost	-	-	0% (of capital cost) ⁸⁴
Retail power price	-	-	0.36 US\$/kWh ^{e91} (2016)

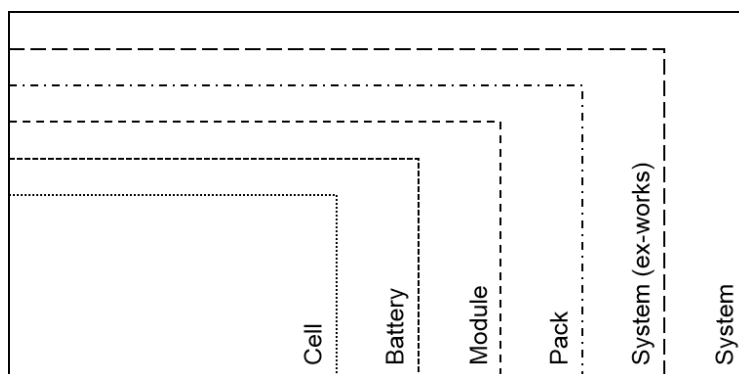
^{*}Capacity x Price = 30 kWh x 330 US\$/kWh (reduces over time as function of ER)

^{**}r parameter from equation 4 (see Supplementary Figure 8)

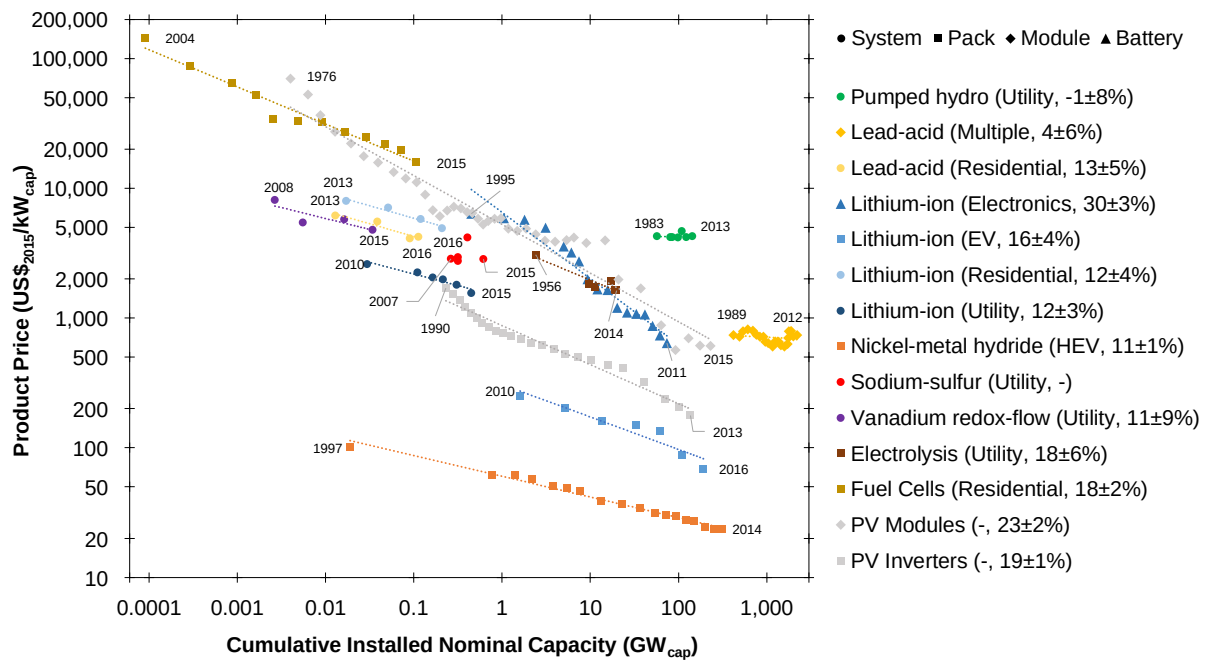
^{***}Distance per capacity / (Capacity * Depth of discharge) = 107 miles / (30kWh * 80%)

^{****}See Supplementary Figure 11

Supplementary Figure 1. Technology scope of electrical energy storage technologies.

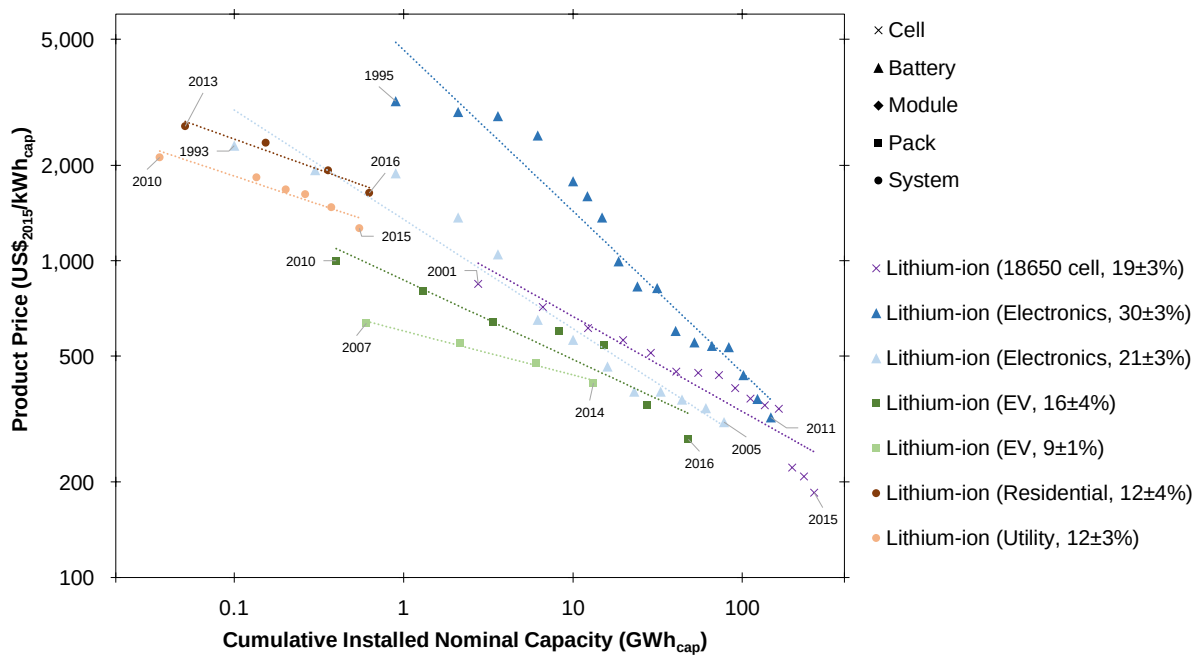


Supplementary Figure 2. Experience curves for EES technologies per power capacity.



Experience curves are shown for product prices per nominal power capacity. Top legend indicates technology scope and bottom legend denotes technology (including application and experience rate with uncertainty). Indicative C-rates (Supplementary Table 1) were used to convert prices and capacity from energy to power terms and vice versa. Solar PV module⁴ and PV inverter³ experience curves are shown for reference.

Supplementary Figure 3. Lithium-ion experience curves for varying technology scopes.



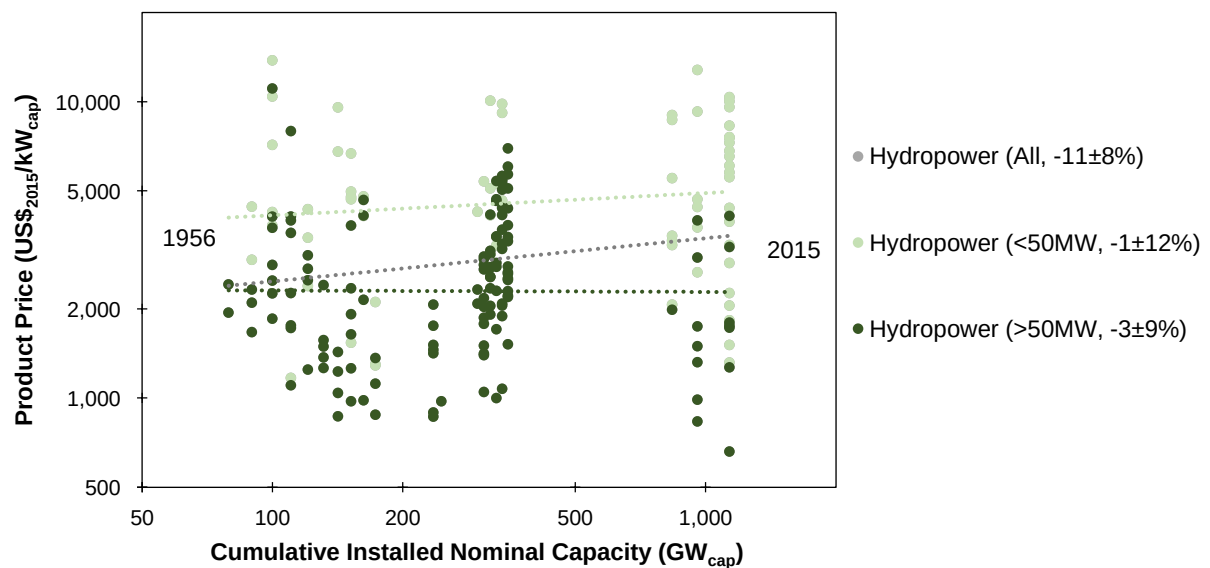
Experience curves for cells, batteries, packs and systems indicate that cost reductions can mainly be attributed to reductions in cell costs and to a lesser extent to additional components required in packs and systems (see components in Supplementary Table 2), given that ERs are highest for cells and batteries and lowest for packs and systems.

Stronger cost reduction for consumer electronics batteries compared to 18650 cells could reflect the ongoing shift from cylindrical 18650 to more cost-competitive prismatic and laminate cells used for consumer electronics batteries²⁸.

Strong cost reduction for 18650 cells in 2013, 2014 and 2015 might be the result of increased demand in EV packs, partly driven by Tesla²⁸.

Data Sources: Lithium-ion (18650 cell, 19±3%)⁹², Lithium-ion (Electronics, 21±3%)⁹³, Lithium-ion (Electronics, 30±3%)^{26–28}, Lithium-ion (EV, 16±4%)²⁹, Lithium-ion (EV, 9±1%)³¹, Lithium-ion (Residential, 12±3%)^{19,20}, Lithium-ion (Utility, 12±3%)^{14,32}.

Supplementary Figure 4. Experience curves for hydropower generation technology.



Historic price^{8–10,94} and cumulative deployment^{95,96} data are analysed for hydropower generation plants. This is done in light of the potential applicability of additional insights to pumped hydro storage due to the similarity of both technologies.

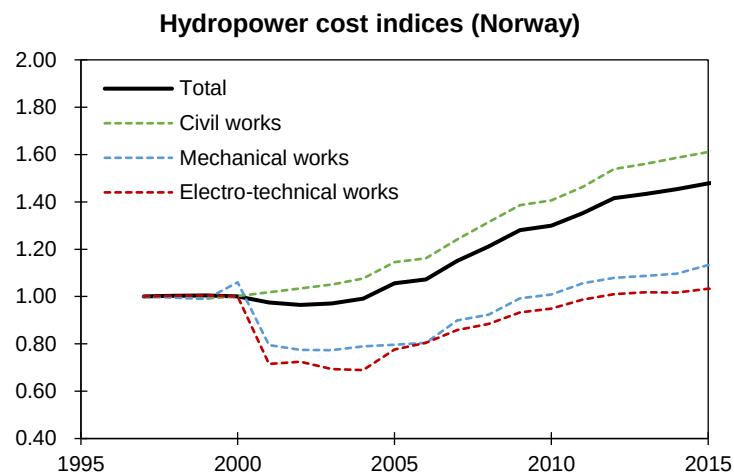
Project price data of hydropower plants from 1956 to 2015 reveal an overall negative experience rate of $-11\pm 8\%$ ($N=204$, $R^2=0.033$, $p=0.010$, $\sigma=0.056$). Separating into small (<50 MW) and large (>50 MW) shows that prices of small hydropower plants tend to increase less at a negative ER of $-1\pm 12\%$ ($N=59$, $R^2=0.001$, $p=0.839$, $\sigma=0.089$) compared to large hydropower plants at $-3\pm 9\%$ ($N=145$, $R^2=0.003$, $p=0.509$, $\sigma=0.067$). The increased construction of small hydropower plants compared to large ones drives the overall, highly negative experience rate.

Potential reasons for the observed price increases have been named as⁹⁴:

- Higher cost of more difficult and remote sites
- Increased development time required due to the necessity of public hearings and licensing
- Increased cost of environmental mitigation
- Increased cost escalation and interest during construction

Due to the similarity between hydropower generation and pumped hydro storage technology, it is conceivable that these factors are also applicable to pumped hydro projects and equally drive the project prices.

Supplementary Figure 5. Cost indices for hydropower cost components.

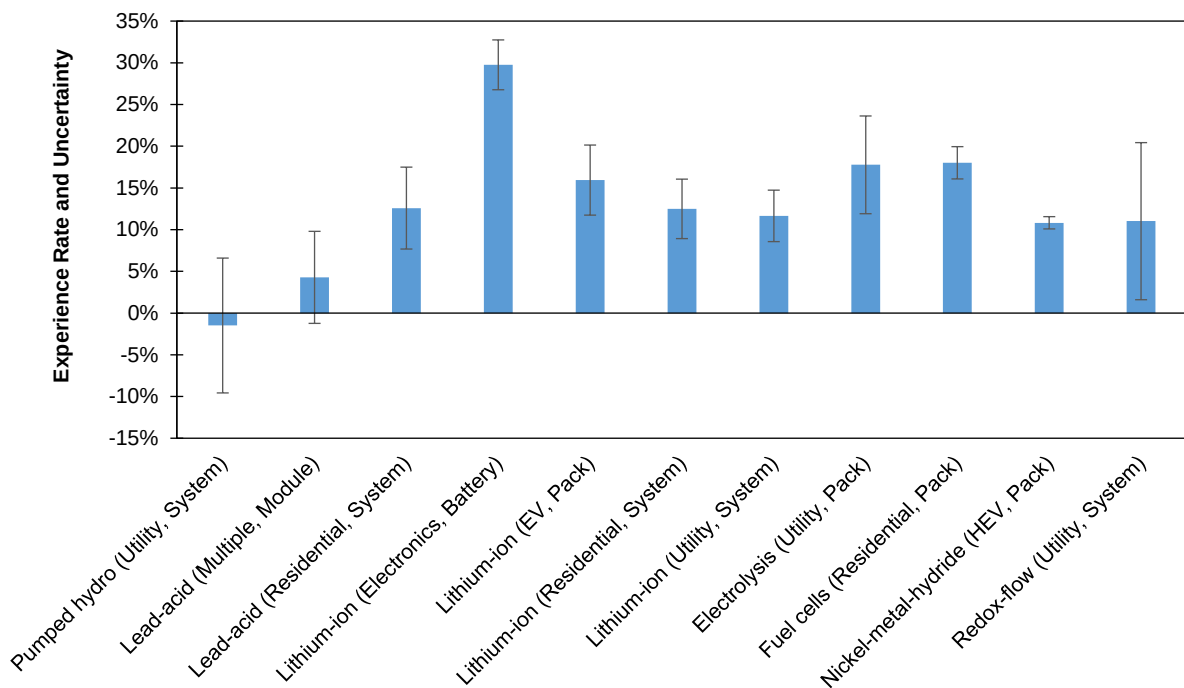


These cost indices refer to hydropower plant prices in Norway⁹⁷. Project costs are disaggregated into three categories: civil, mechanical and electro-technical works, and adjusted for inflation.

The analysis reveals that increasing prices are most likely driven by the costs of the civil works. This confirms the reasons for the price increases outlined in Supplementary Figure 4, since civil works (dam construction, reservoir preparation) are affected by sites that are more difficult to access, environmental mitigation measures and cost escalations during the construction period. It is conceivable that this effect is less pronounced for small compared to large hydropower installations, given that the former benefits from the use of simpler civil structures due to low water flows and low associated risks⁹⁴, leading to smaller relative cost proportion of civil works.

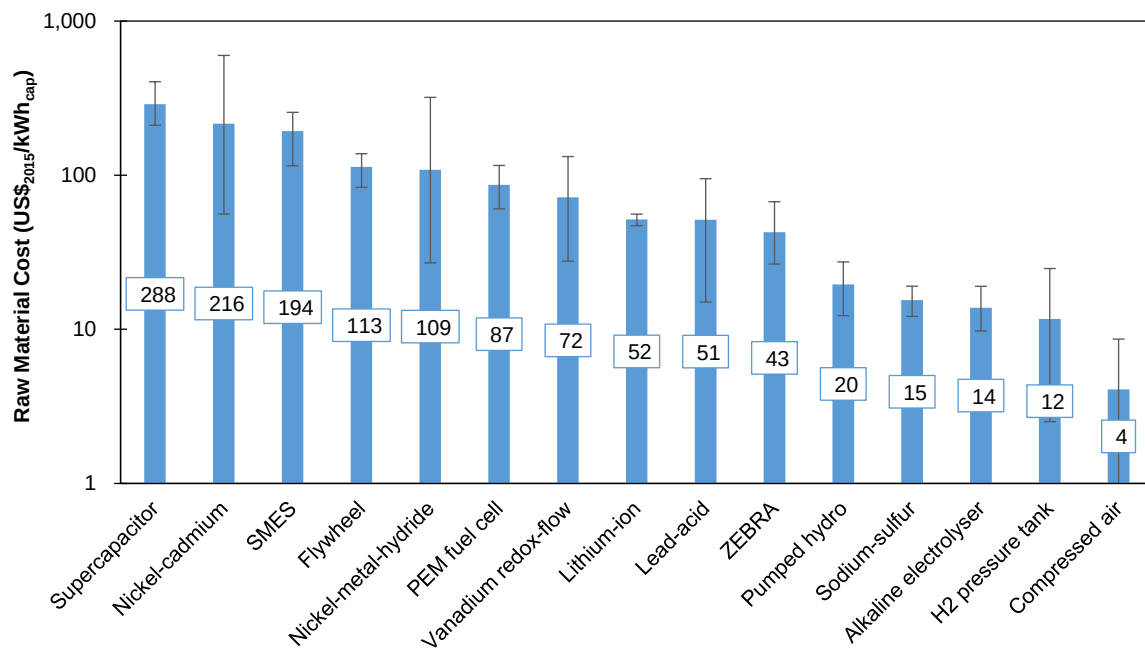
Regardless of size, the parallel that can be drawn from the comparison to hydropower is that capital costs for pumped hydro installations appear to increase due to the increase in civil works costs. This can be a result of more difficult and remote sites, increased development time due to public hearings and licensing and increased environmental protection requirements.

Supplementary Figure 6. Visualisation of experience rate and uncertainty.



This chart shows the experience rates of EES technologies (blue bars) and their uncertainty (error bars). The experience rates are based on the linear regression of the logarithms of product price and cumulative deployment data. Error bars mark minimum and maximum experience rates based on 95% standard error confidence interval of the regression. This uncertainty reflects the deviation of historic product price and cumulative deployment data from the mean experience rate.

Supplementary Figure 7. Cost analysis of raw material inputs for EES technologies.



We calculate the raw material cost for each technology by multiplying material inventories from the literature^{61–63,65,66} with commodity prices of the past 10 years (see Supplementary Table 3).

The blue bars show the raw material cost of EES technologies per system for pumped hydro and compressed air and per pack for all other technologies. The error bars account for variations in each technology's material inventory and commodity prices over the past 10 years.

The analysis shows that those technologies for which ERs are derived in this study exhibit average raw material costs below 110 US\$/kWh (nickel-metal hydride). Higher average material costs can be attributed to technologies designed for high power applications for which we did not derive experience curves. These require expensive materials to withstand extreme conditions: high electric charge for supercapacitors; low temperatures for superconducting magnetic energy storage (SMES); or high velocities for flywheels. Nickel-based batteries exhibit relatively high costs and are subject to high commodity price sensitivity, with raw material costs of 300 US\$/kWh in the worst case for nickel-metal hydride. The material costs of other electrochemical storage technologies are also driven by their active materials like platinum, vanadium, lithium and lead and lie between 15 and 90 US\$/kWh. Mechanical storage technologies have the lowest material costs below 20 US\$/kWh due to the extreme volumes of energy stored.

Wadia et. all explore the raw material cost of the active materials of five of the technologies investigated in this study (vanadium redox-flow, lithium-ion (LMO), lead-acid, sodium-nickel-chloride (ZEBRA), sodium-sulfur)⁹⁸. Their finding of 90 \$US/kWh for vanadium redox-flow matches our range of 28 – 132 US\$/kWh, because in this technology the active materials comprise ~90% of overall raw material costs (see Supplementary Table 4). Regarding lithium-ion (LMO), we find that active materials make up 75% of the total raw material cost of a battery pack. The difference in our findings (75% of 47 - 56 US\$/kWh vs. 1 US\$/kWh⁹⁸) mainly results from our consideration of spherical graphite and battery-grade lithium carbonate needed for battery electrode manufacturing as opposed to flake graphite and extraction-grade lithium carbonate. For lead-acid, the active material also accounts for 75% of the total raw material cost of a battery pack. The difference in our findings (75% of 15 – 95 US\$/kWh vs. 10 US\$/kWh⁹⁸) are subject to significant variations in lead prices. Active

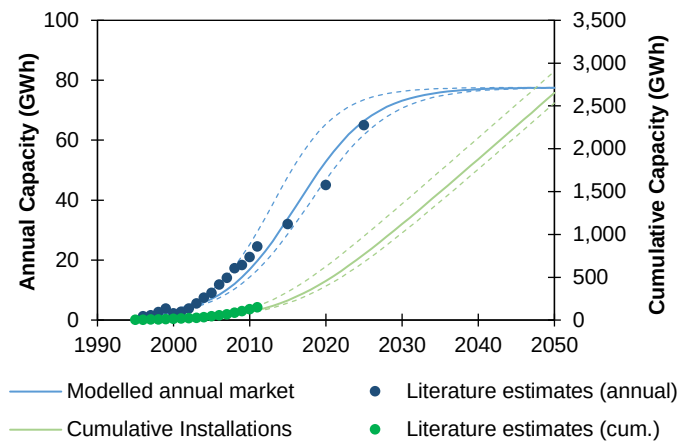
material costs for sodium-nickel-chloride (ZEBRA) battery packs are determined by nickel, comprising between 50% and 60%. Here, the difference (50% of 27 – 67 US\$/kWh vs. 10 US\$/kWh⁹⁸) could be the result of differing assumptions on the nickel requirements per kWh_{cap}. Finally, for sodium-sulfur battery packs, findings on active material costs are within similar ranges, however, raw material costs of the complete battery pack (12 – 19 US\$/kWh vs. 0.1 US\$/kWh) are significantly higher due to the low relative cost proportion comprised by the active materials (<1%).

Additional costs for other factors of production: direct labour, overhead, sales, R&D, depreciation, profit and warranty, are below 20% of final system price for electrochemical technologies at high annual production volumes^{55,99}. For mechanical storage such as pumped hydro, costs for planning, civil works, infrastructure and logistics dominate total costs at 50 - 80%¹⁰⁰. Adding these cost contributions to the raw material cost for nickel-metal hydride and pumped hydro, the electrochemical and mechanical technologies with highest material costs, yields 130 US\$/kWh (32 – 384 US\$/kWh when accounting for ER uncertainty) and 98 US\$/kWh (64 – 135 US\$/kWh when accounting for ER uncertainty) respectively. This is below the price ranges we forecast at 1 TWh cumulative installed capacity. Therefore, these experience curve based price projections are not infeasible.

Supplementary Figure 8. Sigmoid (S-curve type) growth models for EES technologies

To obtain potential EES technology diffusion curves, we derive sigmoid functions (S-curves) for EES application subgroups. We fit the growth rate to annual market capacity forecasts from the literature using non-linear regression. This also yields the standard error of the growth rate to measure goodness-of-fit. Minimum and maximum growth rate are based on a Monte-Carlo analysis of the non-linear regression. Initial and saturation capacity are based on the literature or own assumptions.

a) Consumer Electronics



Key parameters:

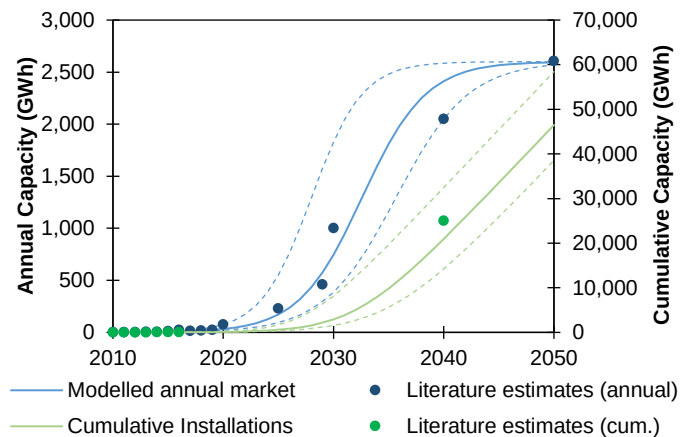
- Growth rate: 0.204
- Standard error: 0.004
- Min growth rate = 0.190
- Max growth rate = 0.241

Assumptions:

- Initial capacity: 1.0 GWh p.a. (1995²⁶)
- Saturation capacity: 77.6 GWh p.a. (2050)
- Literature estimates^{26,28}

Comment: Li-ion battery market for portable devices to double by 2025²⁸

b) Electric Vehicles



Key parameters:

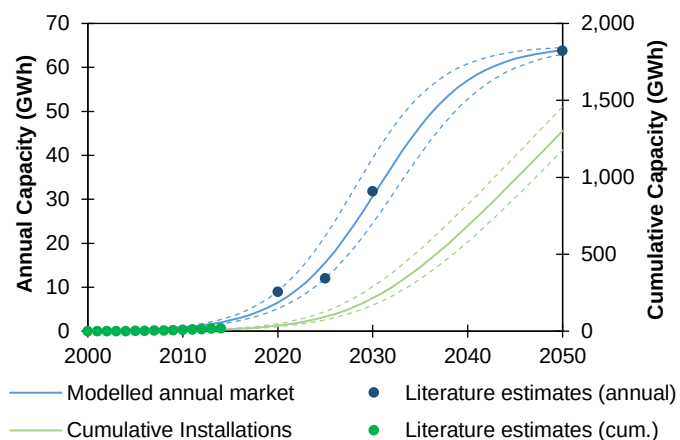
- Growth rate: 0.348
- Standard error: 0.008
- Min growth rate = 0.306
- Max growth rate = 0.436

Assumptions:

- Initial capacity: 1.0 GWh p.a. (2011²⁹)
- Saturation capacity: 2,600 GWh p.a. (2050¹⁰¹)
- Literature estimates^{29,101-103}

Comment: EV sales up from 0.46mn (2015) to 15mn (2030) and 41mn (2040)¹⁰²

c) Hybrid Electric Vehicles



Key parameters:

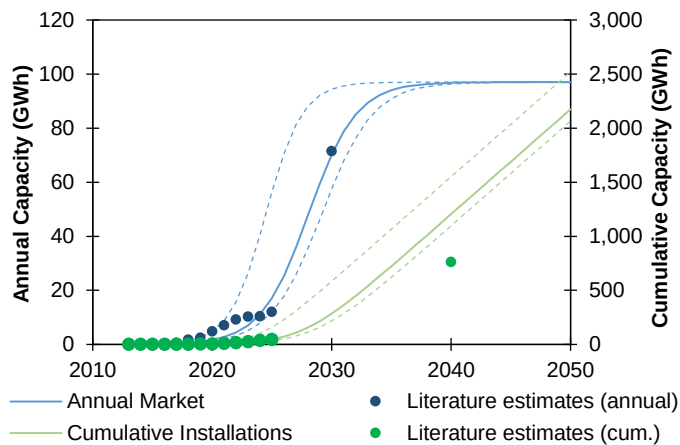
- Growth rate: 0.208
- Standard error: 0.004
- Min growth rate = 0.197
- Max growth rate = 0.225

Assumptions:

- Initial capacity: 0.06 GWh p.a. (1998³⁴)
- Saturation capacity: 65 GWh p.a. (2050¹⁰¹)
- Literature estimates^{28,34,101}

Comment: HEV sales up from 5mn (2015) to 25mn (2030) and 50mn (2050)¹⁰¹

d) Residential Storage



Key parameters:

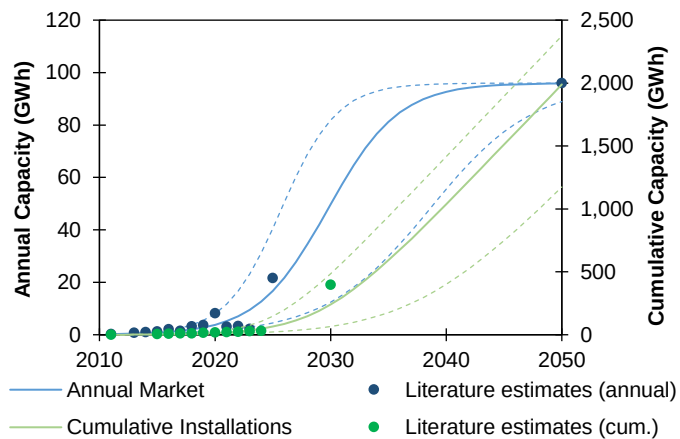
- Growth rate: 0.500
- Standard error: 0.007
- Min growth rate = 0.466
- Max growth rate = 0.656

Assumptions:

- Initial capacity: 0.05 GWh p.a. (2013)
- Saturation capacity: 97 GWh p.a. (2050¹⁰⁴)
- Literature estimates^{105–108}

Comment: 4 GW (~12 GWh) of residential systems installed annually by 2025¹⁰⁵

e) Utility-scale Storage:



Key parameters:

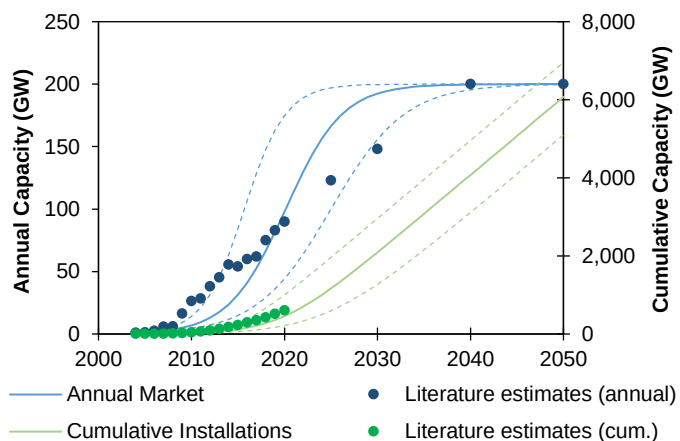
- Growth rate: 0.326
- Standard error: 0.013
- Min growth rate = 0.222
- Max growth rate = 0.425

Assumptions:

- Initial capacity: 0.21 GWh p.a. (2011¹⁴)
- Saturation capacity: 96 GWh p.a. (2050¹⁰⁴)
- Literature estimates^{14,103,104,108,109}

Comment: 30 GWh cumulative installed storage in grid applications by 2025¹⁰⁸

f) Solar Photovoltaic



Key parameters:

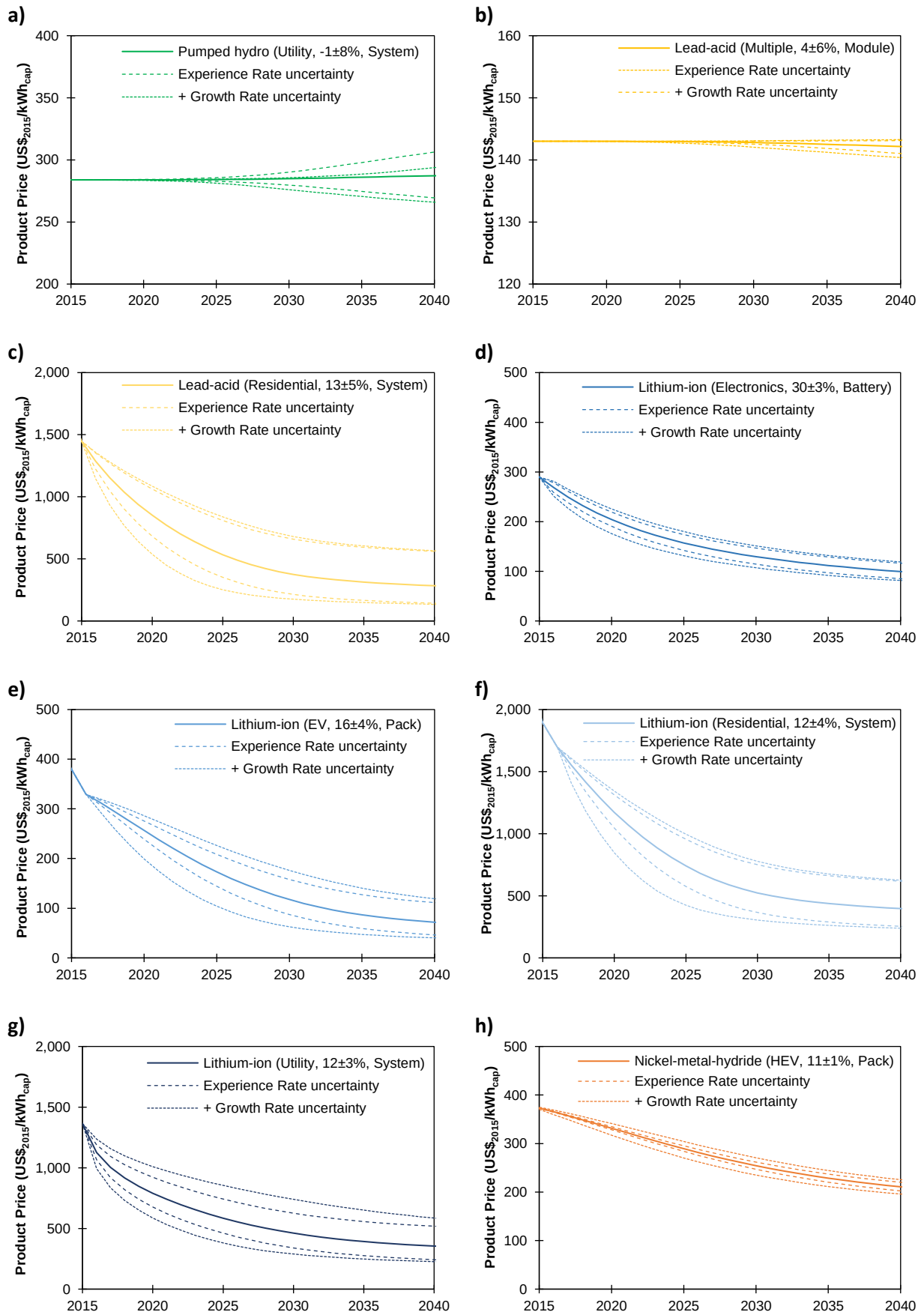
- Growth rate: 0.328
- Standard error: 0.013
- Min growth rate = 0.252
- Max growth rate = 0.452

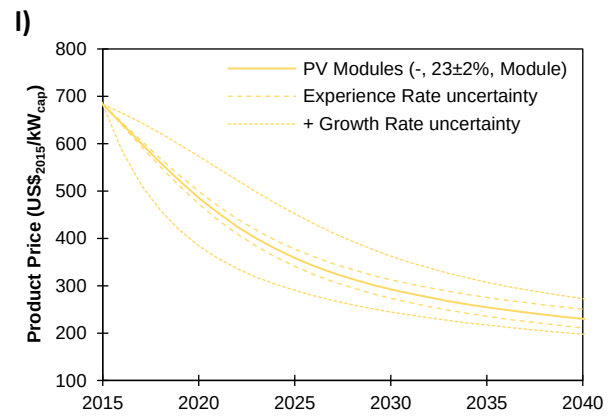
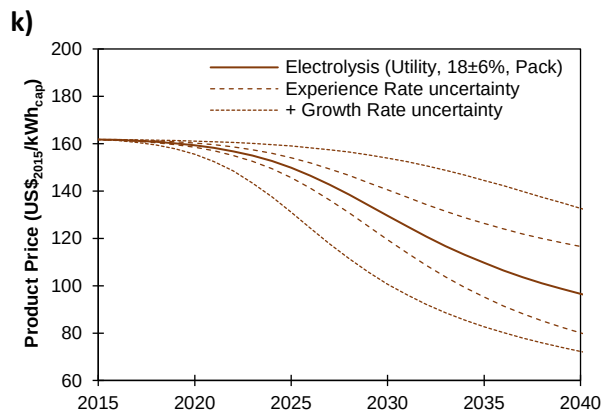
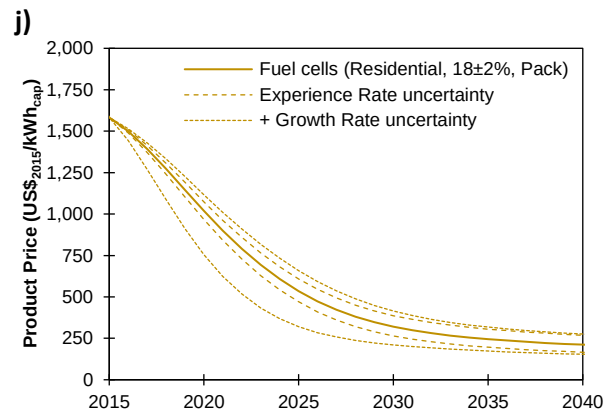
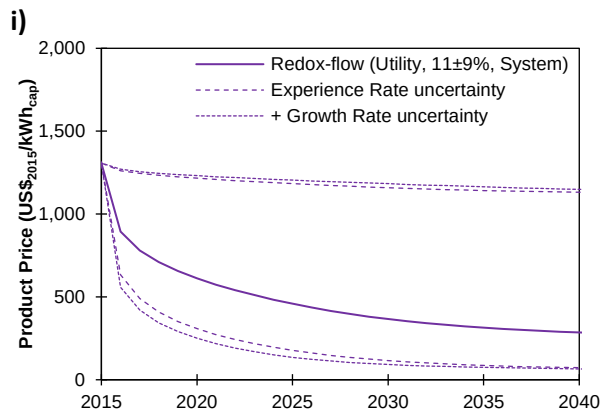
Assumptions:

- Initial capacity: 1 GW p.a. (2004⁴)
- Saturation capacity: 200 GWh p.a. (2050¹¹⁰)
- Literature estimates^{4,110–112}

Comment: Total PV capacity installed each year peaks at 200 GW between 2025 and 2040¹¹⁰

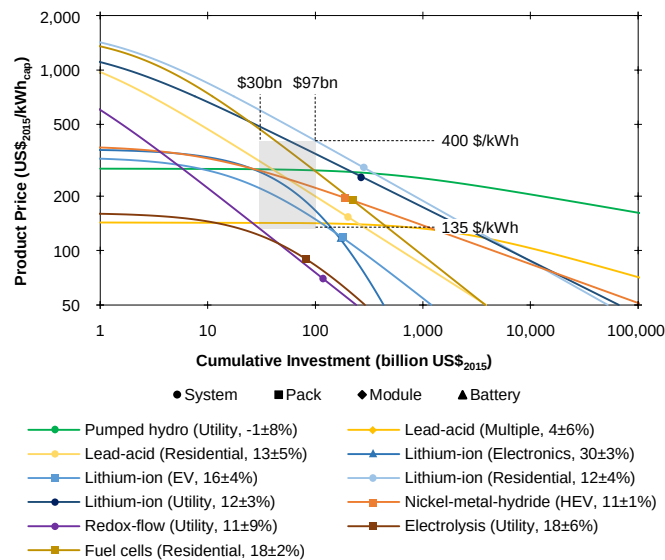
Supplementary Figure 9. Impact of experience rate and additional growth rate uncertainty on timeframe of potential cost reductions for each EES technology.





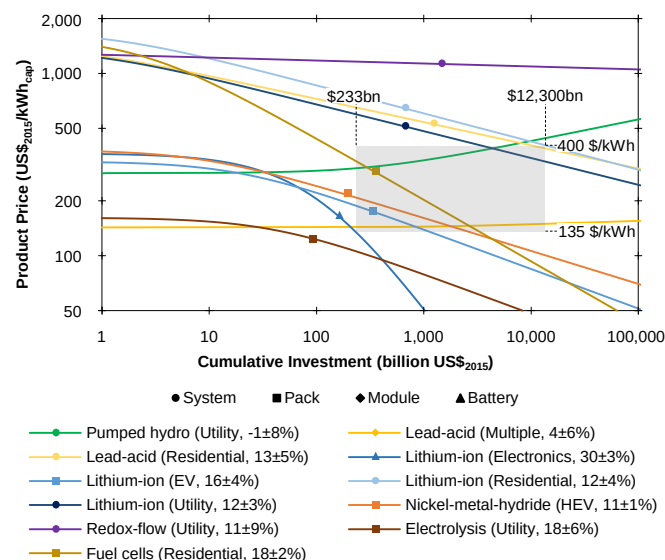
Supplementary Figure 10. Impact of experience rate uncertainty on cumulative investment requirements in deployment to achieve cost reductions.

a) High experience rate scenario



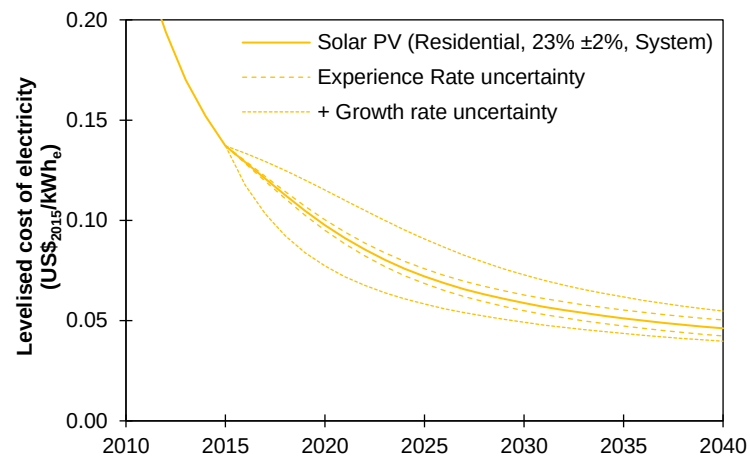
Shaded rectangle indicates investment required to achieve prices of 135 – 400 US\$/kWh. Symbols mark the amount of investment required to deploy 1 TWh cumulative capacity for each technology. No symbol means 1 TWh cumulative capacity is already deployed (pumped hydro, lead-acid modules). Legend denotes technology (including application and experience rate with uncertainty). Symbols: circle – system, square – pack, diamond – module, triangle – battery.

b) Low experience rate scenario



Shaded rectangle indicates investment required to achieve prices of 135 – 400 US\$/kWh. Technologies with positive experience rates (i.e. increasing costs) and redox-flow systems not considered. Symbols mark the amount of investment required to deploy 1 TWh cumulative capacity for each technology. No symbol means 1 TWh cumulative capacity is already deployed (pumped hydro, lead-acid modules). Legend denotes technology (including application and experience rate with uncertainty). Symbols: circle – system, square – pack, diamond – module, triangle – battery.

Supplementary Figure 11. Projected levelised cost of electricity (LCOE) for residential solar PV.



In this analysis, we follow the approach described by the IEA¹⁰ to calculate LCOE and project future PV module prices using the experience curves identified by BNEF⁴. PV module costs are scaled to installed system costs using actual data for residential installations compiled by the IEA¹⁰ (Factor: 2.95). This assumes that the same cost reduction rate applies to soft costs (e.g. installation) as to the module development.

Supplementary References

1. Wright, T. P. Factors Affecting the Cost of Airplanes. *J. Aeronaut. Sci.* **3**, 122–128 (1936).
2. Junginger, M., van Sark, W. & Faaij, A. *Technological learning in the energy sector: Lessons for policy, industry and science. Technological Learning in the Energy Sector: Lessons for Policy, Industry and Science* (Edward Elgar Publishing, 2010).
3. Fraunhofer. *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems*. (Fraunhofer ISE/ Agora Energiewende, 2015).
4. Liebreich, M. Bloomberg New Energy Finance Summit 2016. (2016). Available at: <https://data.bloomberglp.com/bnef/sites/4/2016/04/BNEF-Summit-Keynote-2016.pdf>. (Accessed: 1st May 2016)
5. *Perspectives on experience*. (Boston Consulting Group, 1970).
6. Ferioli, F., Schoots, K. & van der Zwaan, B. C. C. Use and limitations of learning curves for energy technology policy: A component-learning hypothesis. *Energy Policy* **37**, 2525–2535 (2009).
7. Abernathy, W. J. & Kenneth, W. Limits of the learning curve. *Harv. Bus. Rev.* **Sept-Oct**, 109–119 (1974).
8. *Projected Costs of Generating Electricity - Update 2005*. (International Energy Agency, 2005).
9. *Projected Costs of Generating Electricity - 2010 Update*. (International Energy Agency, 2010).
10. *Projected Costs of Generating Electricity - 2015 Edition*. (International Energy Agency, 2015).
11. Jamasb, T. Technical Change Theory and Learning Curves: Patterns of Progress in Electricity Generation Technologies. *Energy J.* **28**, 51–71 (2007).
12. Huff, G. et al. *DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA. Sandia Report* (Sandia National Laboratories, 2013).
13. Jinyue Yan. *Handbook of Clean Energy Systems, 6 Volume Set*. (Wiley-Blackwell, 2015).
14. Sandia National Laboratories. DOE Global Energy Storage Database. (2015). Available at: <http://www.energystorageexchange.org/>. (Accessed: 30th January 2016)
15. Matteson, S. & Williams, E. Residual learning rates in lead-acid batteries: Effects on emerging technologies. *Energy Policy* **85**, 71–79 (2015).
16. Thornton, I., Rautiu, R. & Brush, S. *Lead The Facts*. (IC Consultants Ltd, 2001).
17. Exide Technologies. Exide Heavy Duty Batteries. (2015). Available at: <http://www.exide.com/Media/files/Downloads/TransAmer/Transportation Americas Brochures for Download/Exide Heavy Duty Trade Sheet.pdf>. (Accessed: 23rd August 2016)
18. Exide Technologies. Absolyte GP Batteries. (2016). Available at: <http://www.exide.com/as/en/product-solutions/network-power/product/absolyte-gp.aspx>. (Accessed: 15th August 2016)
19. Tepper, M. *Solarstromspeicher-Preismonitor Deutschland 2016 [German]*. (Bundesverband Solarwirtschaft e.V. und Intersolar Europe, 2016).
20. *Batteries for Stationary Energy Storage in Germany: Market Status & Outlook*. (Germany Trade & Invest, 2016).

21. Wedepohl, D. Detail BSW-Solar - Bundesverband Solarwirtschaft e.V. (2017). Available at: <https://www.solarwirtschaft.de/presse/pressemeldungen/pressemeldungen-im-detail/news/ueber-50000-solarbatterien-in-betrieb.html>. (Accessed: 29th May 2017)
22. Lacey, S. How Distributed Battery Storage Will Surpass Grid-Scale Storage in the US by 2020. (2016). Available at: <http://www.greentechmedia.com/articles/read/how-distributed-battery-storage-will-surpass-grid-scale-storage-in-the-us-b>. (Accessed: 30th April 2016)
23. Hockenos, P. Energy Storage Market Outlook 2015. (2015). Available at: <http://www.renewableenergyworld.com/articles/2015/02/energy-storage-market-outlook-2015.html>. (Accessed: 30th May 2016)
24. Kairies, K.-P. et al. *Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher - Jahresbericht 2015 [German]*. (Institut für Stromrichtertechnik und Elektrische Antriebe - RWTH Aachen, 2015).
25. Storage & Smart Grids: Market overview storage systems. *PV Mag.* **08/2014**, 74–77 (2014).
26. Pitt, A., Buckland, R., Antonio, P. D., Lorenzen, H. & Edwards, R. *Citi GPS: Global Perspectives & Solutions - Investment Themes in 2015*. (Citigroup, 2015).
27. Matteson, S. & Williams, E. Learning dependent subsidies for lithium-ion electric vehicle batteries. *Technol. Forecast. Soc. Change* **92**, 322–331 (2015).
28. Pillot, C. The Rechargeable Battery Market and Main Trends 2013-2025. *31st International Battery Seminar & Exhibit* (2014).
29. Sandalow, D., McCormick, C., Rowlands-Rees, T., Izadi-Najafabadi, A. & Orlandi, I. *Distributed Solar and Storage - ICEF Roadmap 1.0*. (Innovation for Cool Earth Forum, 2015).
30. Curry, C. *2016 Lithium-ion Battery Price Survey*. (Bloomberg New Energy Finance, 2016).
31. Nykvist, B. & Nilsson, M. Rapidly falling costs of battery packs for electric vehicles. *Nat. Clim. Chang.* **5**, 329–332 (2015).
32. Hocking, M., Kan, J., Young, P., Terry, C. & Begleiter, D. *F.I.T.T. for investors: Welcome to the Lithium-ion Age*. (Deutsche Bank - Market Research, 2016).
33. Kalhammer, F. R., Kopf, B. M., Swan, D. H., Roan, V. P. & Walsh, M. P. *Status and prospects for zero emissions vehicle technology - Report of the ARB independent expert panel 2007*. (State of California Air Resources Board, 2007).
34. Toyota Motor Corporation. With 8 Million Units Sold, Toyota Proves Hybrids Have Staying Power. (2015). Available at: <http://newsroom.toyota.co.jp/en/detail/9163695>. (Accessed: 30th April 2016)
35. Prius Battery Specifications. (2013). Available at: <http://www.toyotapriusbattery.com/>. (Accessed: 16th August 2016)
36. EVsRoll.com. Hybrid Car Statistics. (2012). Available at: http://evsroll.com/Hybrid_Car_Statistics.html. (Accessed: 16th August 2016)
37. Gerssen-Gondelach, S. J. & Faaij, A. P. C. Performance of batteries for electric vehicles on short and longer term. *J. Power Sources* **212**, 111–129 (2012).
38. SAE International. Don't count NiMH power out, says battery guru. (2010). Available at: <http://articles.sae.org/7666/>. (Accessed: 30th April 2016)
39. Tortora, A. C. Experiences and Initial results from Terna's Energy Storage Projects. *7th Grid+Storage Workshop* (2015). Available at: <http://www.gridplusstorage.eu/workshops/6-workshop-7-croatia-italy-malta-slovenia-switzerland>. (Accessed: 21st July 2016)

40. Rial, P. Sodium-Sulfur Battery Powers NGK's Unique Wind Energy. (2008). Available at: <http://www.bloomberg.com/news/articles/2008-04-10/sodium-sulfur-batteries-power-ngk-insulators-unique-wind-energy>. (Accessed: 16th August 2016)
41. NAS Battery Energy Storage System. 1–29 (2013). Available at: http://www.eei.org/meetings/Meeting_Documents/Abe.pdf. (Accessed: 21st July 2017)
42. Cost Reduction Roadmap for NAS. Obtained from manufacturer: 11th August 2016.
43. Indicative Manufacturer Quote. Obtained: 17/03/2016 at Energy Storage Trade Show in Dusseldorf, Germany.
44. Mizutani, T. *Battery Energy Storage for Increasing Renewable Energy*. (NGK Insulators Ltd., 2015).
45. NGK Insulator Ltd. History of NAS Battery Development. (2016). Available at: <https://www.ngk.co.jp/nas/why/history.html>. (Accessed: 16th August 2016)
46. Staubly, R. & McHugh, J. *Vanadium Redox Battery Demonstration Program*. (US Department of Energy, 2013).
47. Schoots, K., Ferioli, F., Kramer, G. J. & van der Zwaan, B. C. C. Learning curves for hydrogen production technology: An assessment of observed cost reductions. *Int. J. Hydrogen Energy* **33**, 2630–2645 (2008).
48. Smolinka, T., Günther, M. & Garche, J. *Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien [German]. NOW-Studie* (Fraunhofer ISE/FCBAT, 2011).
49. Steinmüller, H. et al. *Power to Gas – eine Systemanalyse. Markt- und Technologiescouting und -analyse. [German]*. (Johannes Kepler Universität Linz/ Montanuniversität Leoben/ TU Wien, 2014).
50. Staffell, I. & Green, R. The cost of domestic fuel cell micro-CHP systems. *Int. J. Hydrogen Energy* **38**, 1088–1102 (2013).
51. Hydrogenics Investor Presentation January 2014. (2014). Available at: <http://www.hydrogenics.com/docs/default-source/pdf/investor-presentation-jan-14.pdf?sfvrsn=2>. (Accessed: 20th July 2016)
52. Staffell, I. *Fuel Cells for Domestic Heat and Power: Are they worth it?* (PhD Thesis, University of Birmingham, 2009).
53. Dodds, P. et al. *The Role of Hydrogen and Fuel Cells in Providing Affordable, Secure Low-Carbon Heat*. (H2FC Supergen, 2014).
54. Hart, D., Lehner, F., Rose, R., Lewis, J. & Klippenstein, M. *The Fuel Cell Industry Review 2015*. (E4Tech, 2015).
55. Argonne National Laboratory. BatPac Version 3.0. *Excel Spreadsheet* (2015). Available at: <http://www.cse.anl.gov/batpac/about.html>. (Accessed: 1st December 2015)
56. Cluzel, C. & Douglas, C. *Cost and performance of EV batteries: Final report for The Committee on Climate Change*. (Element Energy, 2012).
57. Ortiz, L. *Grid-Scale Energy Storage Balance of Systems 2015-2020: Architectures, Costs and Players*. (GTM Research, 2015).
58. Cobb, J. GM Says Li-ion Battery Cells Down To \$145/kWh and Still Falling. (2015). Available at: <http://www.hybridcars.com/gm-ev-battery-cells-down-to-145kwh-and-still-falling/>. (Accessed: 30th April 2016)

59. Indicative manufacturer Quote. Obtained: 17/03/2016 at Energy Storage Trade Show in Dusseldorf, Germany.
60. Bloomberg Professional [Online]. Subscription Service. Available at: www.bloomberg.com. (Accessed: 20th July 2016)
61. Ashby, M. F. & Polyblank, J. *Materials for Energy Storage Systems—A White Paper*. (Granta Design, 2012).
62. Sullivan, J. L. & Gaines, L. Status of life cycle inventories for batteries. *Energy Convers. Manag.* **58**, 134–148 (2012).
63. Notter, D. a., Kouravelou, K., Karachalios, T., Daletou, M. K. & Haberland, N. T. Life cycle assessment of PEM FC applications: electric mobility and μ -CHP. *Energy Environ. Sci.* **8**, 1969–1985 (2015).
64. Dunn, J B; Gaines, L; Barnes, M; Sullivan, J; Wang, M. Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle. *J. Chem. Inf. Model.* **53**, 1689–1699 (2013).
65. Galloway, R. C. & Dustmann, C.-H. ZEBRA Battery - Material Cost Availability and Recycling. in *Proceeding of the international electric vehicle symposium (EVS-20)* 19–28 (2003).
66. Koj, J. C., Schreiber, A., Zapp, P. & Marcuello, P. Life Cycle Assessment of Improved High Pressure Alkaline Electrolysis. *Energy Procedia* **75**, 2871–2877 (2015).
67. Zhang, W., Ren, F., Feng, Z. & Wang, J. *Manufacturing Cost Analysis of Novel Steel / Concrete Composite Vessel for Stationary Storage of High-Pressure Hydrogen*. (Oak Ridge National Laboratory, 2012).
68. Mori, M., Jensterle, M., Mržljak, T. & Drobnič, B. Life-cycle assessment of a hydrogen-based uninterruptible power supply system using renewable energy. *Int. J. Life Cycle Assess.* **19**, 1810–1822 (2014).
69. Fürstenwerth, D. et al. *Stromspeicher in der Energiewende [German]*. (Agora Energiewende, 2014).
70. Darling, R. M., Gallagher, K. G., Kowalski, J. A., Ha, S. & Brushett, F. R. Pathways to low-cost electrochemical energy storage: a comparison of aqueous and nonaqueous flow batteries. *Energy Environ. Sci.* **7**, 3459–3477 (2014).
71. Qnovo. 30. COST, COST AND COST. (2014). Available at: <http://qnovo.com/cost-cost-and-cost/>. (Accessed: 27th August 2016)
72. Catenacci, M., Verdolini, E., Bosetti, V. & Fiorese, G. Going electric: Expert survey on the future of battery technologies for electric vehicles. *Energy Policy* **61**, 403–413 (2013).
73. Wesoff, E. How Soon Can Tesla Get Battery Cell Costs Below \$100 per Kilowatt-Hour? 2016 Available at: <https://www.greentechmedia.com/articles/read/How-Soon-Can-Tesla-Get-Battery-Cell-Cost-Below-100-per-Kilowatt-Hour>. (Accessed: 27th August 2016)
74. Feldman, D. et al. *Exploring the Potential Competitiveness of Utility-Scale Photovoltaics plus Batteries with Concentrating Solar Power, 2015 – 2030*. (National Renewable Energy Laboratory, 2016).
75. Viswanathan, V. et al. Cost and performance model for redox flow batteries. *J. Power Sources* **247**, 1040–1051 (2014).
76. Bertuccioli, L. et al. *Fuel cells and hydrogen Joint undertaking Development of Water Electrolysis in the European Union*. (E4Tech/ Element Energy, 2014).

77. Ammermann, H. *et al. Advancing Europe's energy systems: Stationary fuel cells in distributed generation*. (Publications Office of the European Union, 2015).
78. *Tank-to-wheels Report: Vehicle retail price estimation*. (European Commission - Joint Research Centre, 2008).
79. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016 - Executive Summary (EPA-420-S-16-001, November 2016)*. (United States Environmental Protection Agency, 2016).
80. 2017 Nissan LEAF Electric Car: 100% Electric. 100% Fun. (2017). Available at: <https://www.nissanusa.com/electric-cars/leaf/>. (Accessed: 17th March 2017)
81. Hill, N. *et al. A review of the efficiency and cost assumptions for road transport vehicles to 2050*. (AEA Technology, 2012).
82. Mould, P. Environmental Comparisons of Steel and Plastic Automotive Fuel Tanks. (2005). Available at: [http://www.autosteel.org/~media/Files/Autosteel/Great Designs in Steel/GDIS 2005/08 - Environmental Comparisons of Steel and Plastic Automotive Fuel Tanks.pdf](http://www.autosteel.org/~media/Files/Autosteel/Great%20Designs%20in%20Steel/GDIS%202005/08%20-%20Environmental%20Comparisons%20of%20Steel%20and%20Plastic%20Automotive%20Fuel%20Tanks.pdf). (Accessed: 27th March 2017)
83. McKerracher, C. & Curry, C. *Used EV batteries for stationary storage: second-life supply & costs*. (Bloomberg New Energy Finance, 2016).
84. Lazard's levelized cost of storage analysis - version 2.0. (2016). Available at: <https://www.lazard.com/media/438042/lazard-levelized-cost-of-storage-v20.pdf>. (Accessed: 26th January 2017)
85. US Department of Energy. U.S. Gasoline and Diesel Retail Prices. Available at: https://www.eia.gov/dnav/pet/PET_PRI_GND_DCUS_NUS_M.htm. (Accessed: 17th March 2017)
86. US Department of Energy. Electric Power Monthly - with data for December 2016. (2017). Available at: <https://www.eia.gov/electricity/monthly/pdf/epm.pdf>. (Accessed: 17th March 2017)
87. Steady State Vehicle Charging Fact Sheet: 2015 Nissan Leaf Vehicle Specifications. *Advanced Vehicle Testing* (2015). Available at: <https://avt.inl.gov/sites/default/files/pdf/fsev/SteadyStateLoadCharacterization2015Leaf.pdf>. (Accessed: 17th March 2017)
88. Hoppmann, J., Volland, J., Schmidt, T. S. & Hoffmann, V. H. The economic viability of battery storage for residential solar photovoltaic systems - A review and a simulation model. *Renew. Sustain. Energy Rev.* **39**, 1101–1118 (2014).
89. Battery Capacity Loss Warranty Chart For 2016 30 kWh Nissan LEAF. Available at: <http://insideevs.com/battery-capacity-loss-chart-2016-30-kwh-nissan-leaf/>. (Accessed: 17th March 2017)
90. Mayr, F. & Beushausen, H. Navigating the maze of energy storage costs. *PV Magazine* **05/2016**, 84–88 (2016).
91. Verivox. Verbraucherpreisindex Strom: Kostenentwicklung für Privatkunden [German]. Available at: <http://www.verivox.de/verbraucherpreisindex-strom/>. (Accessed: 17th March 2017)
92. Anderson, N. & Rosser, J. *Berenberg Thematics : Battery adoption at the tipping point*. (Berenberg Bank, 2016).
93. Liebreich, M. Global Trends in Clean Energy Investment Clean Energy Ministerial. (2013).

Available at:

http://www.cleanenergyministerial.org/Portals/2/pdfs/BNEF_presentation_CEM4.pdf.
(Accessed: 29th August 2015)

94. Gordon, J. L. Hydropower Cost Estimates. *Water Power Dam Constr.* **11/1983**, 30–37 (1983).
95. World hydropower statistics | International Hydropower Association. (2017). Available at: <https://www.hydropower.org/world-hydropower-statistics>. (Accessed: 20th March 2017)
96. Gordon, J. L. Recent Developments in Hydropower. *Water Power & Dam Construction* **9/1983**, 21–23 (1983).
97. The Norwegian Water Resources and Energy Directorate (NVE). Index HP 1982-2016. Obtained: 22nd March 2017.
98. Wadia, C., Albertus, P. & Srinivasan, V. Resource constraints on the battery energy storage potential for grid and transportation applications. *J. Power Sources* **196**, 1593–1598 (2011).
99. James, B. D., Moton, J. M. & Colella, W. G. *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2013 Update*. (Strategic Analysis, 2014).
100. *Renewable Energy Technologies: Cost Analysis Series - Hydropower*. (International Renewable Energy Agency, 2012).
101. *Electric and Plug-in Hybrid Roadmap*. (International Energy Agency, 2010).
102. MacDonald, J. Electric vehicles to be 35% of global new car sales by 2040. *Bloomberg New Energy Finance* (2016). Available at: <http://about.bnef.com/press-releases/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/>. (Accessed: 19th August 2016)
103. Jaffe, S. The Battery Industry: Global Market Sizing and Forecast. (2015). Available at: <http://benchmarkminerals.com/toronto/sam-jaffe.pdf>. (Accessed: 25th October 2016)
104. *Technology Roadmap - Energy Storage*. (International Energy Agency, 2014).
105. Navigant Research. Global Annual Deployments of Residential Energy Storage Systems are Expected to Increase from 94.9 MW in 2016 to 3,773.3 MW in 2025. (2016). Available at: <https://www.navigantresearch.com/newsroom/global-annual-deployments-of-residential-energy-storage-systems-are-expected-to-increase-from-94-9-mw-in-2016-to-3773-3-mw-in-2025>. (Accessed: 19th August 2016)
106. Rubel, H. & Pieper, C. *Revisiting Energy Storage*. (Boston Consulting Group, 2011).
107. McCrone, A. McCrone: How has energy's long term changed in the last year? (2016). Available at: <https://about.bnef.com/blog/mccrone-energys-long-term-changed-last-year/>. (Accessed: 25th October 2016)
108. Goldie-Scot, L. *GLOBAL ENERGY STORAGE FORECAST, 2016-24*. (Bloomberg New Energy Finance, 2016).
109. Navigant Research. Power Capacity of Global Installed Energy Storage for the Grid and Ancillary Services is Expected to Reach 21.6 GW in 2025. (2016). Available at: <https://www.navigantresearch.com/newsroom/power-capacity-of-global-installed-energy-storage-for-the-grid-and-ancillary-services-is-expected-to-reach-21-6-gw-in-2025>. (Accessed: 25th November 2016)
110. *Technology Roadmap - Solar Photovoltaic Energy*. (International Energy Agency, 2014).
111. Kurz, J. Global PV's Five Year Outlook. (2015). Available at: <http://www.apricum-group.com/global-pvs-five-year-outlook-going-from-strength-to-strength/>. (Accessed: 23rd August 2016)

112. Liebreich, M. Keynote - Bloomberg New Energy Finance Summit 2015. (2015). Available at: <https://data.bloomberglp.com/bnef/sites/4/2015/04/BNEF-2015-Keynote-ML.pdf>. (Accessed: 29th August 2015)