Implications of Energy Storage

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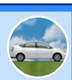
McKinsey&Company

We identified energy storage and its applications as one of the twelve game changing clean technologies five years ago

Six technologies have the potential to affect US energy productivity by 2015

1	**Unconven-tional oil and natural-gas production**	▪ In 2011, at $3 per Mcf and with abundant supply, saves US consumers billions and enables US to reduce its GHG emissions ▪ And now the same for oil	▪ **Needs to address water and disposal challenges but can reshape global resource eco-nomics as Europe, China, and India also begin to evaluate and tap their resources**
2	**Electric Vehicles** 	▪ Rapid battery cost decline from $1,000/kWh in 2009, to $500/kWh in 2010, and $350/kWh in 2012E ▪ 1-2mn EVs sold today	▪ **At $100/kWh battery cost, EVs will match ICE up front cost. Expected sales of 15-20mn/yr, consumer savings of $500bn/yr and other benefits** ▪ **Zinc may be even better than Li**
3	**Advanced internal combustion engines** 	▪ Current US corporate average fuel standard of 27.5mpg will rise to 35.5mpg in 2016 and 54.5 in 2025	▪ **Technology available today** ▪ **Peak gasoline demand reached in US in 2008**
4	**Solar Photovoltaics** 	▪ 2011 cost of $3/watt, down from $8/watt in 2009. With 40% growth, 2015E cost $2/w and <$1/w in 2020	▪ **At this cost, most new homes and big box commercial businesses in high insolation areas will prefer solar over traditional power sources**
5	**LED Lighting** 	▪ In 2011, 100 lumen LED cost $20 down from $50 in 2009 ▪ $8 bulb at 170l/W here in 18 months – better than CFL ▪ Lighting accounts for almost 15% of US electricity demand	▪ **LED expected to account for 30% of global lighting in 2015 and 80% in 2020, saving consumers $100bn annually & resulting in 1.5% decline in US electricity demand/yr** ▪ **Lighting will integrate wireless, sensors, speakers**
6	**Waste recycling** 	▪ 10x more gold in e-waste than gold ore ▪ Municipal waste if separated early is a profit center	▪ **Recent Lexus is 90% recyclable** ▪ **Aluminum infinitely recyclable and 80% cheaper**

Six more technologies should drive change by 2020

7	**Grid-scale storage** 	▪ $150-200/kWh grid storage is economical in all major metro areas requiring > 100GW of storage in US by 2020, and making delivery of solar, wind, nuclear & coal much cheaper
8	**Digital power conversion** 	▪ High speed, digital, silicon-carbide switches should be able to deliver same results for less than 1/10th the cost and 1% of the weight and footprint
9	**Compressor-less air conditioning & electro-chromic windows** 	▪ New compressor-less air-conditioning and electro-chromic window technologies offer the potential to cut home heating and cooling bills in half[1,2]
10	**Clean coal** 	▪ Oxycombustion provides retrofit solution. Further clean coal innovations (e.g. using advanced bio-enzymes) could keep most of coal plants in operation for years ▪ $8,000-$10,000/kW current cost of CCS expected to decline to $2,000/kW
11	**Bio and Electro-fuels** 	▪ At $100/barrel, biofuels are already growing rapidly. Cellulosic and algae-based biofuels overcome agrable land constraints. Potential to deliver at $2/gallon or less by 2020 ▪ Main question now is scalability of production
12	**Water treatment** 	▪ 80% of world population in areas of water shortage by 2030 ▪ Water underpriced globally but already causing energy and food shortages ▪ New selective membranes bring waste water and salt water treatment costs into commercial viability by 2020

SOURCE: McKinsey

Energy storage was also highlighted on the McKinsey Global Institute list of technologies with the biggest economic impact over next decade

Mobile Internet
Increasingly inexpensive and capable mobile computing devices and Internet connectivity

Automation of knowledge work
Intelligent software systems that can perform knowledge work tasks involving unstructured commands and subtle judgments

The Internet of Things
Networks of low-cost sensors and actuators for data collection, monitoring, decision making, and process optimization

Cloud technology
Use of computer hardware and software resources delivered over a network or the Internet, often as a service

Advanced robotics
Increasingly capable robots with enhanced senses, dexterity, and intelligence used to automate tasks or augment humans

Autonomous and near-autonomous vehicles
Vehicles that can navigate and operate with reduced or no human intervention

Next-generation genomics
Fast, low-cost gene sequencing, advanced big data analytics, and synthetic biology (“writing” DNA)

Energy storage
Devices or systems that store energy for later use, including batteries

3D printing
Additive manufacturing techniques to create objects by printing layers of material based on digital models

Advanced materials
Materials designed to have superior characteristics (e.g., strength, weight, conductivity) or functionality

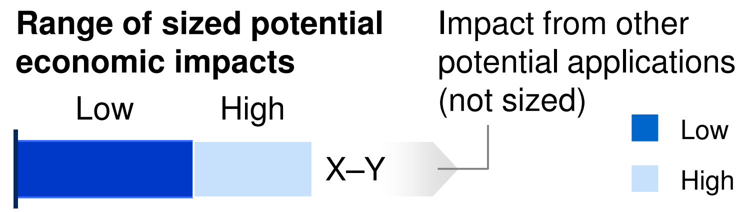
Advanced oil and gas exploration and recovery
Exploration and recovery techniques that make extraction of unconventional oil and gas economical

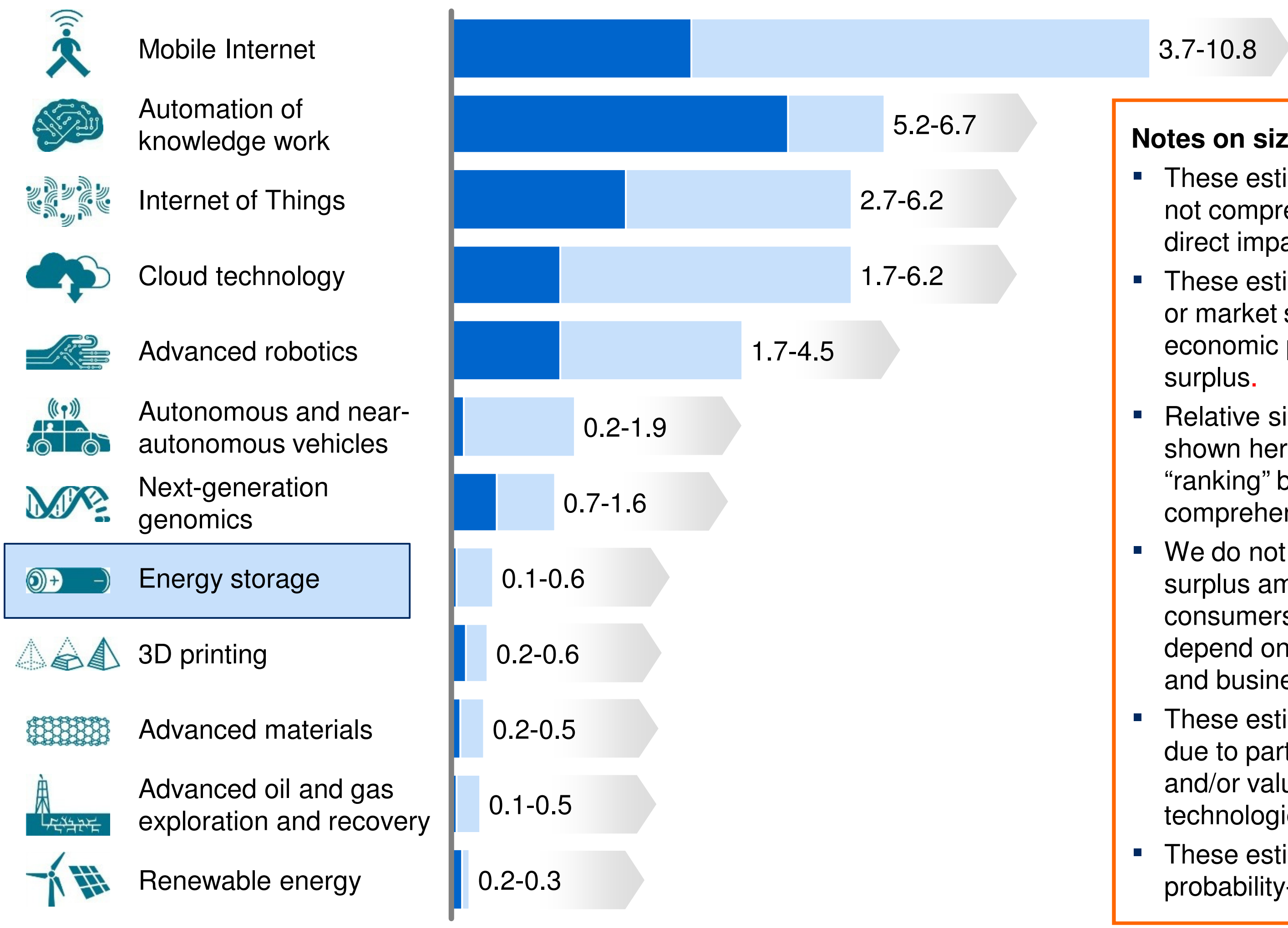
Renewable energy
Generation of electricity from renewable sources with reduced harmful climate impact

SOURCE: McKinsey Global Institute analysis

Estimated potential economic impact of technologies from sized applications in 2025, including consumer surplus

$ trillion, annual





Notes on sizing

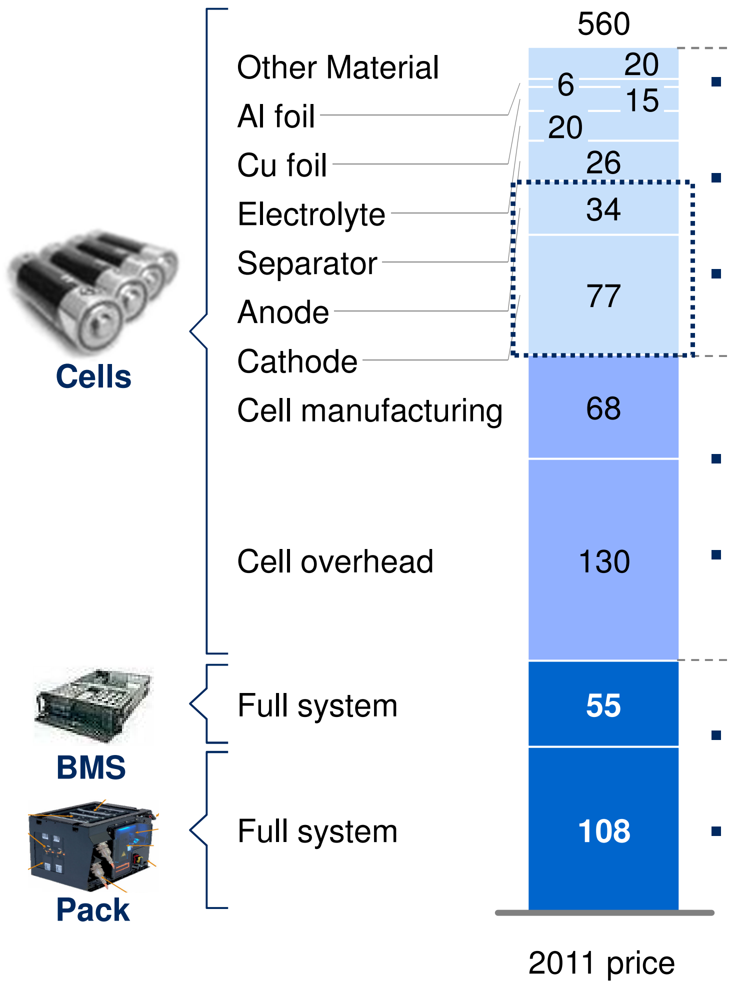
- These estimates of economic impact are not comprehensive and include potential direct impact of sized applications only.
- These estimates do not represent GDP or market size (revenue), but rather economic potential, including consumer surplus.
- Relative sizes of technology categories shown here cannot be considered a "ranking" because our sizing is not comprehensive.
- We do not quantify the split or transfer of surplus among or across companies or consumers. Such transfers would depend on future competitive dynamics and business models.
- These estimates are not directly additive due to partially overlapping applications and/or value drivers across technologies.
- These estimates are not fully risk- or probability-adjusted.

SOURCE: McKinsey Global Institute analysis

Batteries have come down in cost by 50% in the last 5 years – but are still expensive – about $25K for Tesla base model

Battery pack price, 2011
USD/kWh

- Cell materials
- Cell assembly
- Pack & BMS



- Cell materials are the most significant single price component of the battery
- The active materials – anode and cathode – together make up about 50% of the material cost
- Much of the R&D spending today is focused on increasing the capacity of the active materials

- Cell manufacturing today is largely not at scale – next generation plants are 10x the capacity of existing plants
- SG&A, R&D and profit account for about 75% of overhead

- Battery Management Systems are not yet using fully integrated circuit or component designs
- SG&A, R&D and profit account for about 75% of overhead

Note: BMS: battery management system

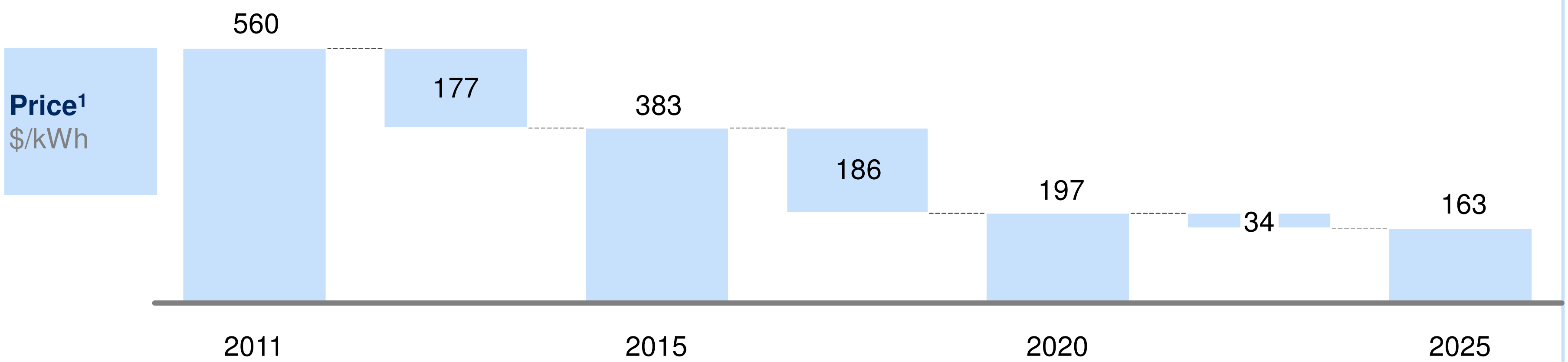
SOURCE: Team analysis

Pack cost could drop to about $200/kWh by 2020 and to about $160/kWh by 2025 – with early lab technologies for $100/kWh in sight

Major source of improvement

Pack price evolution at 70% depth of discharge

Horizon 1 (2011-2015) Economies of scale	Horizon 2 (2016-2020) Technology evolution	Horizon 3 (2021-2025) Continued improvements



"What you need to believe"

Horizon 1 (2011-2015)

- **Manufacturing** volumes increase, spread fixed costs and improve manufacturing processes as plants move from 10-20 packs per year to 100k packs/year
- **Supply chain** matures as material supplier costs decrease and margins shrink from today's 20-40%
- **Technology** improves cell capacity ~10%
- **Yields** improve from 90 to 94%

Horizon 2 (2016-2020)

- **Manufacturing** improves at 3% p.a. (rate seen in auto industry)
- **Supply chain** maturity results in 15% EBIT margins for materials and lower manufacturing costs
- **Technology** sees ~80% improvement in cell capacity over today (layered-layer cathode, Si anode)
- **Yields** improve from 94 to 97%

Horizon 3 (2021-2025)

- **Manufacturing** improves at 3% p.a. (rate seen in auto industry)
- **Technology** sees ~110% improvement in cell capacity over today (layered-layer cathode, Si anode, 4.2V cell voltage)

1 Price is to auto OEM for entire vehicle pack assuming 8.7 kWh (PHEV 20) with pack and BMS, 70% depth of discharge, made on US assembly lines

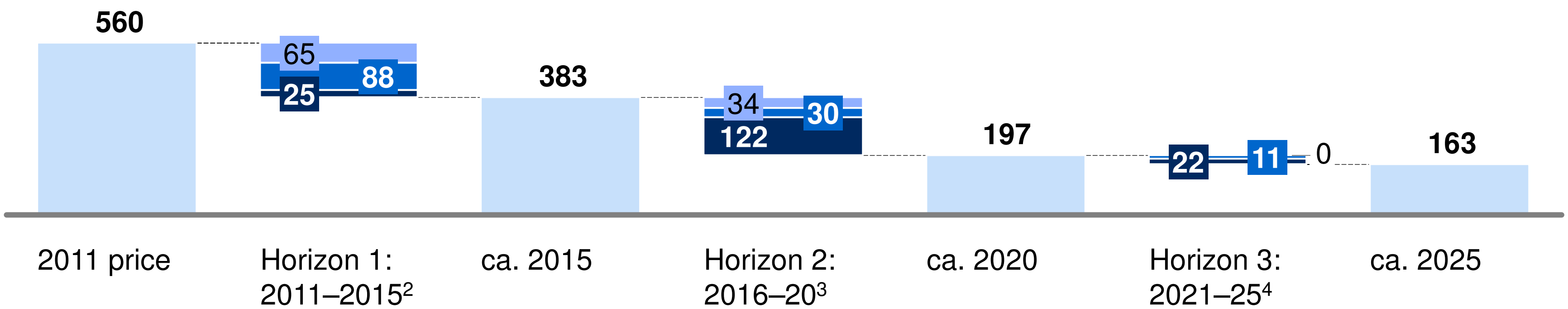
SOURCE: Team analysis

Materials and manufacturing efficiencies will drive most of the price improvements through 2015, technology will be critical thereafter

Material and component cost reductions · Manufacturing and overhead improvements · Technology improvements

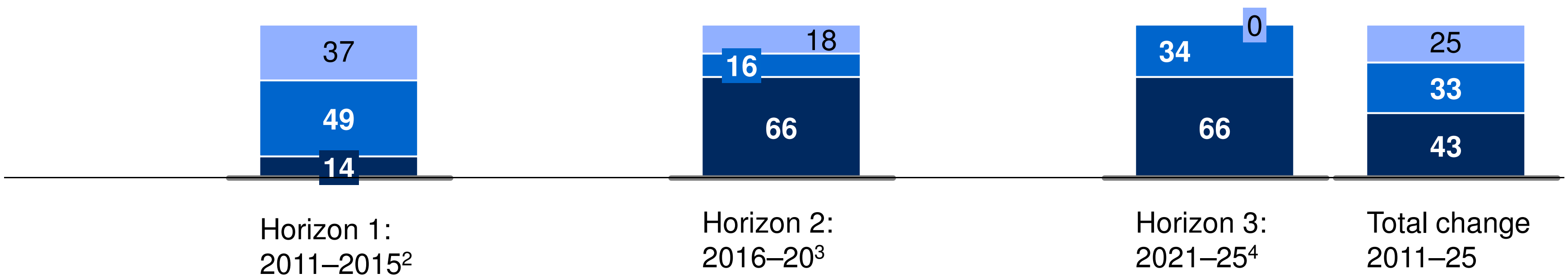
Projected prices of lithium-ion battery packs

(2011 $ per kilowatt-hour)



Price change by category

(%)[1]

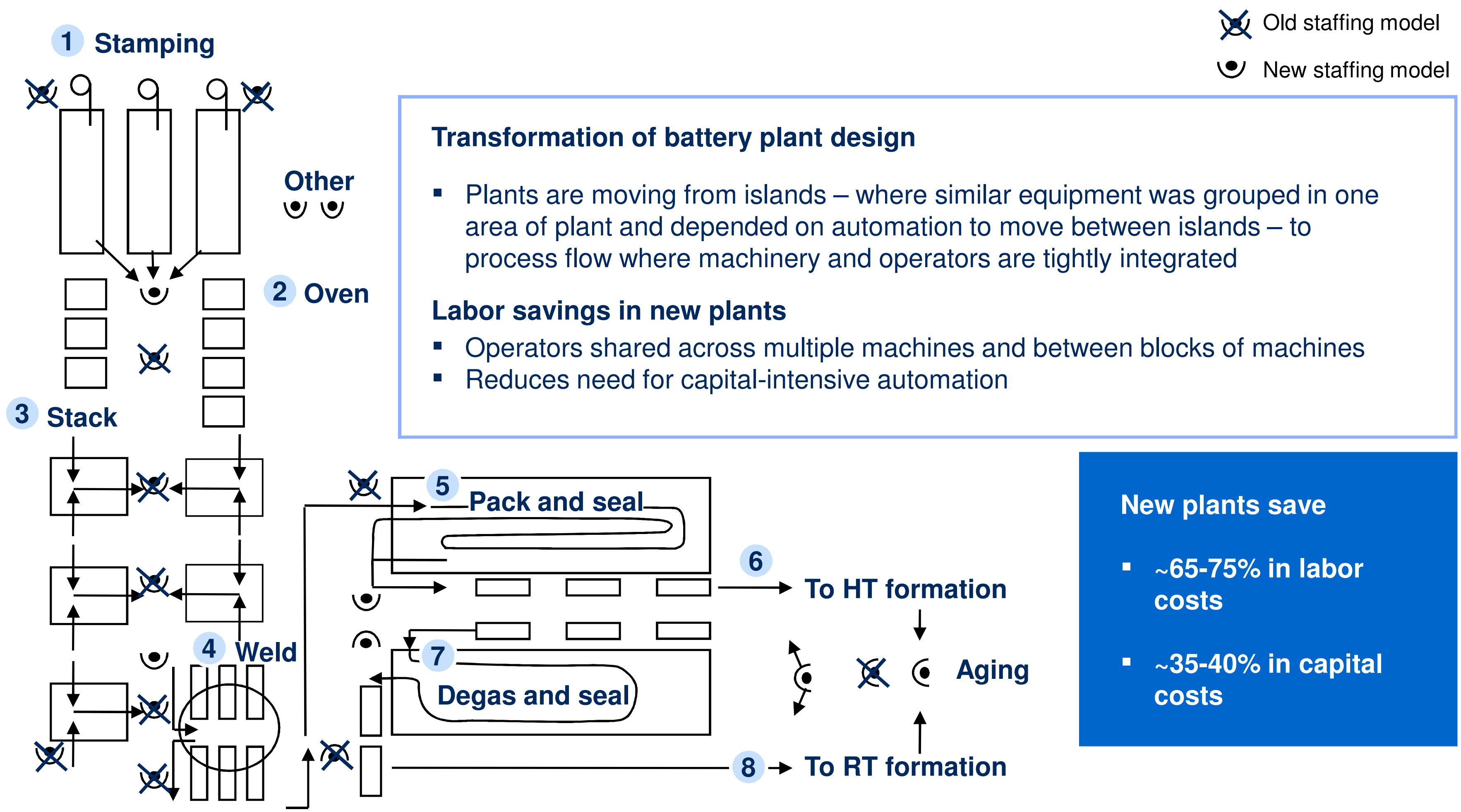


1 Change from previous horizon (%)
2 Assumes: plant scale of 100,000 battery packs per year; cell capacity increase of 10%; expected materials cost and margin compression
3 Assumes: continuous manufacturing improvement of 6% for BMS and 3% for all other pack elements; cell capacity increases 82% from today; expected materials cost and margin compression
4 Assumes: continuous manufacturing improvement of 6% for BMS and 3% for all other pack elements; cell capacity increases 112% from today

SOURCE: Team analysis

Example: lean techniques could reduce labor costs per cell by 67% in a state of the art battery assembly plant

Layout and staffing proposal per shift



Transformation of battery plant design

- Plants are moving from islands – where similar equipment was grouped in one area of plant and depended on automation to move between islands – to process flow where machinery and operators are tightly integrated

Labor savings in new plants

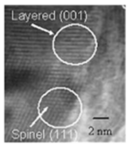
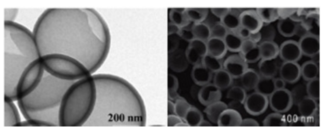
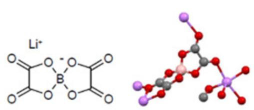
- Operators shared across multiple machines and between blocks of machines
- Reduces need for capital-intensive automation

New plants save

- **~65-75% in labor costs**
- **~35-40% in capital costs**

SOURCE: Team analysis

Medium term technological change is likely to come from three major sources – cathode, anode and electrolyte improvement

Technology[2]	Description	Outlook	Institutions involved[1]
Layered-layered cathode material 	▪ Nano-structured cathode materials allow for higher energy densities	▪ Looked on as promising by all OEMs; BASF and LG Chem both licensed Argonne patent – BASF is building a factory in Ohio to commercialize	Argonne National Laboratory; GM; LG Chem; BASF The Chemical Company
Silicon anodes 	▪ Silicon can carry more Li+ ions per mole than graphite, and therefore has higher energy densities	▪ Likely by 2013 in consumer electronics, but major technical issues around swelling and material stability exist that industry experts expect will delay automotive inclusion until post-2015	Berkeley Lab; Samsung SDI; amprius; Panasonic
High-voltage electrolytes 	▪ Higher-voltage-capable electrolytes allow for higher cell densities	▪ Strong research focus in Korea and Japan in this particular area, because of its large capacity benefits. Improvement by 2020 not clear – DOE predicts will reach market post-2020.	LG Chem; Samsung SDI; A123 Systems; Saft

1 Not exhaustive

SOURCE: EPRI, DOE; team analysis, expert interviews

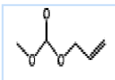
Our views on technology development generally aligns with the US DOE, but are slightly more conservative around electrolyte development

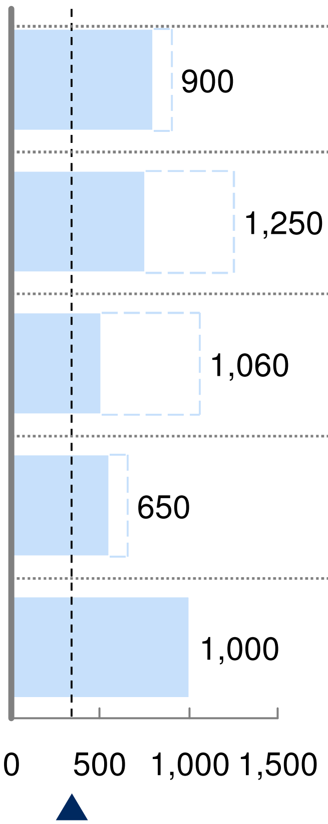
Key difference

Component	Anode	Electrolyte	Cathode
Today's technology	**300 mAh/g** ▪ Graphite ▪ Hard carbon	**4 volt** ▪ Liquid organic solvents and gels	**120-160 mAh/g** ▪ Layered oxides ▪ Spinels ▪ Olivines
Next generation	**600 mAh/g** ▪ Intermetallics (Si) and new binders ▪ Nanophase metal oxides ▪ Conductive additives ▪ Tailored SEI	**5 volt** ▪ High-voltage electrolytes ▪ Electrolytes for Li metal ▪ Nonflammable electrolytes	**300 mAh/g** ▪ Layered-layered oxides ▪ Metal phosphates ▪ Tailored surfaces
DOE timeline	2016-2020	Pre-2020 (key difference)	2015 (key difference)
McKinsey timeline	2016-2020	Post-2020 (key difference)	2016-2020 (key difference)

SOURCE: DOE Vehicle Technologies Program 2011 Annual Merit Review

Various Horizon 3 technological approaches exist in the lab – we have assumed only high-voltage electrolytes are commercialized

	Technology	Specific energy[1] (Wh/kg)	Advantages	Limitations
	High-voltage electrolytes	N/A – voltage change only	▪ Key to many other innovations, such as lithium metal	▪ Have been tried but don't exist in stable form yet
	Advanced Lithium-Ion Intercalation	900	▪ Well understood underlying chemistry ▪ Adopt existing processes	▪ Improved electrolytes ▪ Better surface electrolyte interface needed
	Non-Lithium Intercalation	1,250	▪ Potentially higher specific energy than Li-ion cells	▪ Theoretical potential is controversial amongst chemists
	Lithium-Metal (with intercalation cathodes)	1,060	▪ Can use existing cathode materials ▪ Eliminate cell fade	▪ Safety (no dendrite formation)
	Lithium-Sulfur	650	▪ Low temperature performance	▪ Cycle life (polysulfide elimination, protect anode)
	Lithium-Air	1,000	▪ Potentially very safe	▪ Cycle life ▪ Technical maturity



Panasonic today ~400

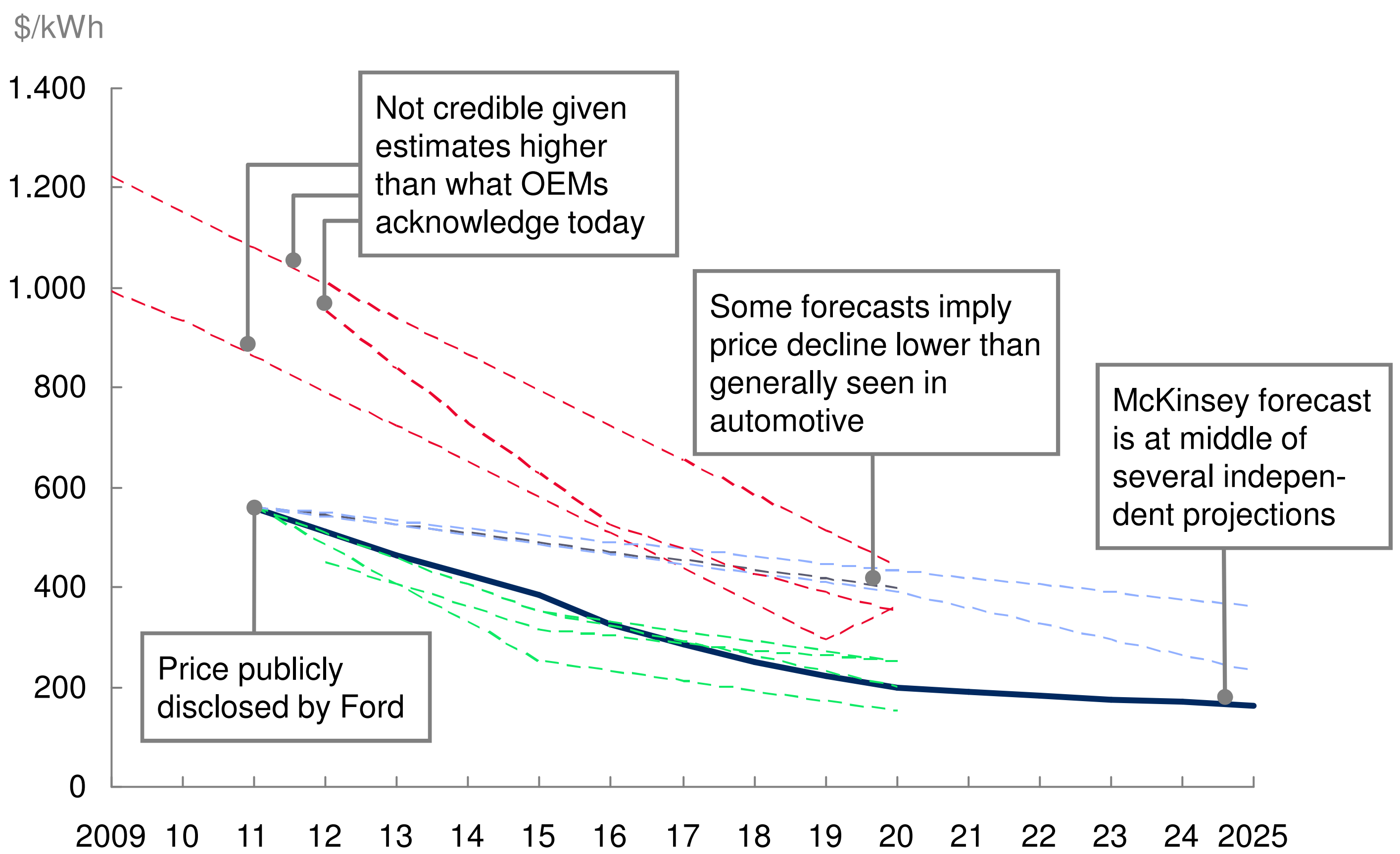
1 Independent validation critical

SOURCE: DOE, expert interviews

Our bottom-up method has resulted in a cost projection on the low end of the range projected by industry observers

McKinsey projection
Other projections[1,2]

Projected battery pack prices $/kWh



- The McKinsey forecast is close to those of other groups, including IHS and Bain
- Forecasts on the high end appear to misread current market battery prices or assume rates of price decline lower than typical of the auto industry

1 Other projections include: BCG (High/Low); Bain (High/Low); Lux research; Pike Research; IHS; Deutsche Bank; ICF; NAS; Bloomberg New Energy Finance
2 Other projections assumed to start at $560/kWh in 2011 if no starting cost projection is given; other projections display assumes straight line change between given projection years

SOURCE: Press search

Sized applications of energy storage could have economic impact of $90 billion to $635 billion per year in 2025, including consumer surplus (1/2)

Sized applications		Potential economic impact of sized applications in 2025 $ billion, annually	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
	Electric and hybrid vehicles	20–415	▪ 115 million passenger vehicles sold ▪ Over 1 billion vehicles in the market	▪ 40–100% of vehicles sold in 2025 could be electric or hybrid	▪ Fuel price: $2.80–7.60 per gallon ▪ 0.22 KWh per mile fuel efficiency for EVs
Distri-buted energy	Stabilizing electricity access	25–100	▪ 13,000 TWh electricity consumption in emerging markets ▪ 2–70 hours per month without electricity	▪ 35–55% adoption with solar and battery combination ▪ 35–55% of companies in Africa, Middle East, and South Asia own diesel generators	▪ $0.75–2.10 per KWh value of uninterrupted power supply to an enterprise ▪ $0.20–0.60 per KWh value per household
Distri-buted energy	Electrifying new areas	0–50	▪ 60–65% rural electrification rate ▪ 1.2 billion people without electricity access ▪ 60 KWh monthly electricity requirement of average household	▪ 50–55% adoption based on number of people projected to earn above $2 per day	▪ $0.20–0.60 per KWh value per household for direct lighting, TV, and radio benefits
	Frequency regulation	25–35			
	Peak load shifting	10–25			
	Infrastructure deferral	~10			
	Other potential applications (not sized)				
	Sum of sized potential eco-nomic impacts	**90–635**			

NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

Sized applications of energy storage could have economic impact of $90 billion to $635 billion per year in 2025, including consumer surplus (2/2)

Sized applications		Potential economic impact of sized applications in 2025 ($ billion, annually)	Estimated scope in 2025	Estimated potential reach in 2025	Potential productivity or value gains in 2025
	Electric and hybrid vehicles	20–415	▪ 27,000–31,000 TWh global electricity consumption ▪ 1.5% electricity production reserved for frequency regulation ▪ 2.5% additional reserved for renewable integration	▪ 100% technology adoption, more efficient, and cost competitive with incumbent solutions	▪ $30 per MWh weighted average frequency-regulation price
	Stabilizing electricity access	25–100			
	Electrifying new areas	0–50			
Utility grid	Frequency regulation	25–35	▪ 12% of total electricity production possible to shift ▪ 850 million tons additional CO_2 release	▪ 10–20% adoption of energy storage, given costs compared with cycle gas turbines	▪ $65–80 per MWh between non-renewable peak and base load ▪ $45–65 per MWh between peak and average wind price ▪ $30–45 per MWh between peak and average solar price
Utility grid	Peak load shifting	10–25			
Utility grid	Infrastructure deferral	~10	▪ $295 billion per year investment in T and D infrastructure deferral ▪ 10% spent to reduce congestion	▪ 15% adoption based on share of transmission lines economical for energy storage	▪ Possible deferral of infrastructure investment by 2.5 years
	Other potential applications (not sized)				
	Sum of sized potential economic impacts	**90–635**			

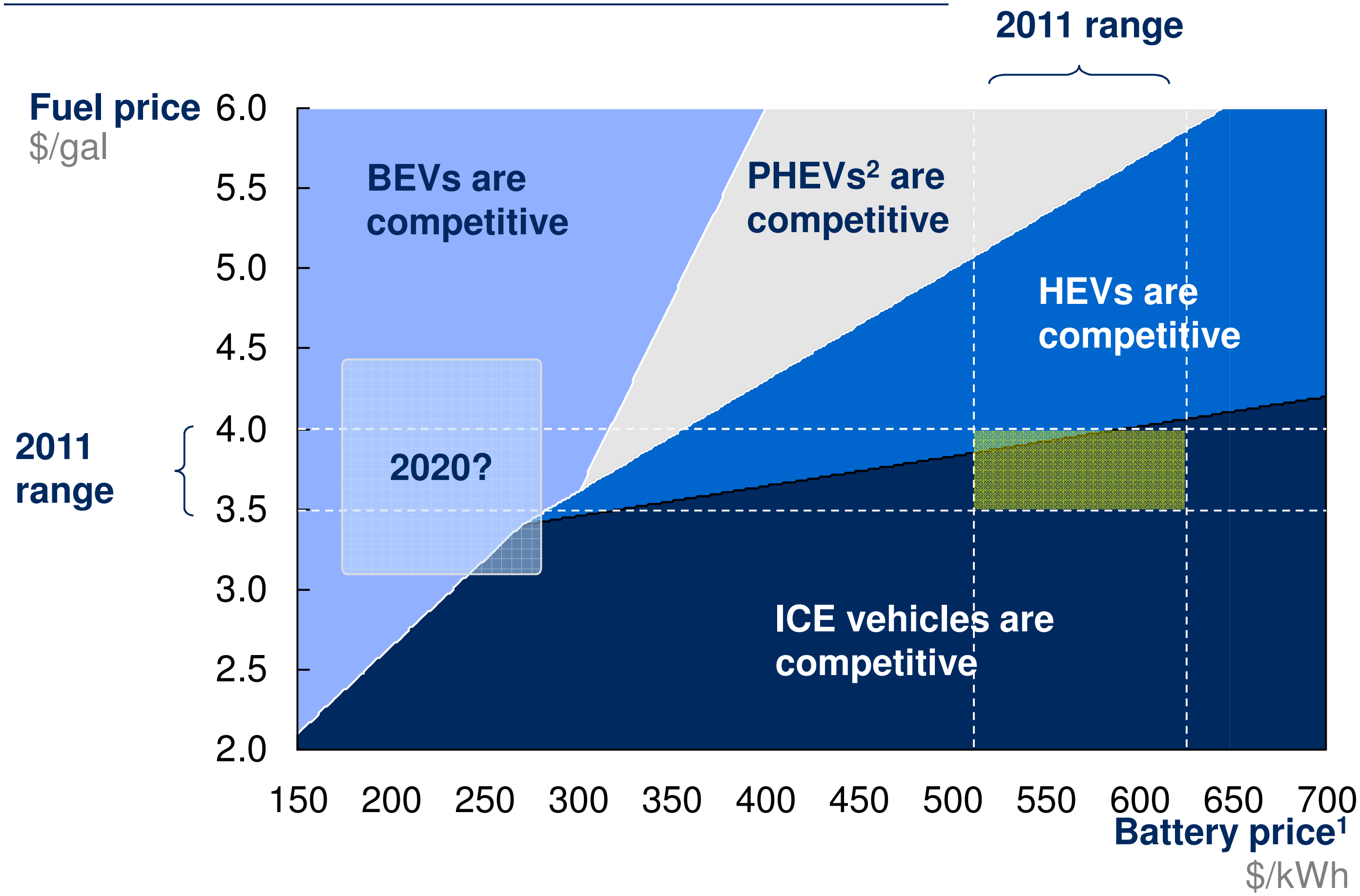
NOTE: Estimates of potential economic impact are for some applications only and are not comprehensive estimates of total potential impact. Estimates include consumer surplus and cannot be related to potential company revenue, market size, or GDP impact. We do not size possible surplus shifts among companies and industries, or between companies and consumers. These estimates are not risk- or probability-adjusted. Numbers may not sum due to rounding.

SOURCE: McKinsey Global Institute analysis

A total cost of ownership analysis shows how, in the United States, energy storage costs below ~$250/kWh could favor BEVs adoption

UNITED STATES EXAMPLE

5-year TCO for different drive train technologies



1 Assumes energy usage of 240 watt hours per mile compared with 305-320 watt-hours per mile today due to e.g., light-weighting, efficient air conditioning; assumes 12,500 vehicle miles travelled per year

2 BEV = Battery electric vehicle; PHEV = plug-in hybrid vehicle; HEV = hybrid vehicle; ICE = internal combustion engine

SOURCE: McKinsey analysis; EIA

OEM technology choices and volume targets provide insight into early positioning relative to the energy storage landscape

LiB
NiMH

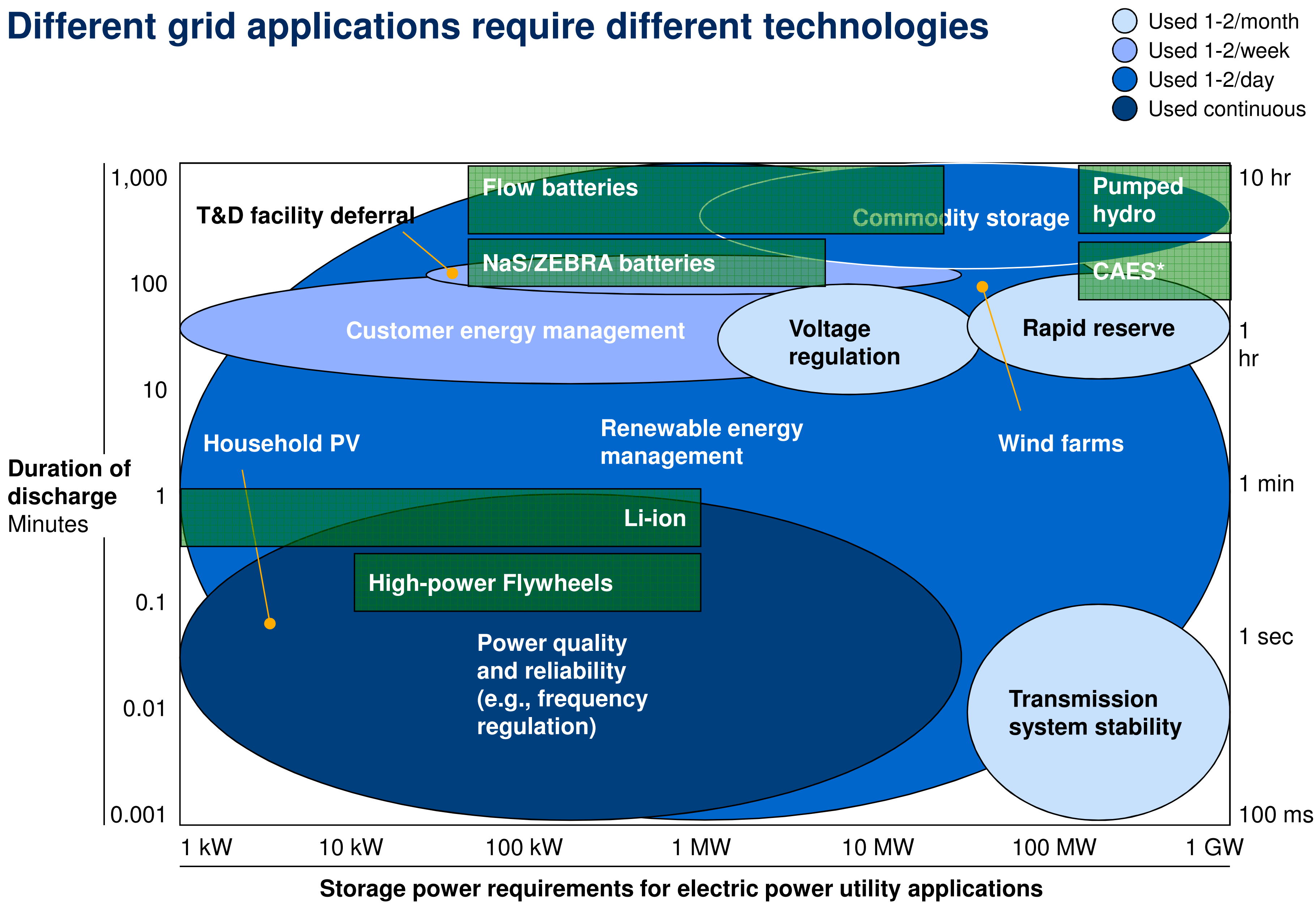
Company	Current behaviors	Announced plan: No. of projects ‘11-’15	Announced plan: Target capacity ‘11-’15, MWh	Announced plan: Target units ‘11-’15, 1,000 units
Toyota	▪ Dominant player in HEV ▪ Will continue to pursue HEV focused strategy	22	9,783	4,835
GM	▪ Showing firm wide big commitment ▪ PHEV is the center of the strategy	11	9,407	1,114
Volkswagen	▪ Plans to commercialize series of EV from 2013 ▪ Significantly investing in R&D	17	10,533	1,298
Ford	▪ Plans to launch Ford Focus (BEV) in 2012 ▪ Pragmatically launching EV with ICE platforms	10	11,173	989
Honda	▪ Leading player in HEV ▪ Will continue to pursue HEV focused strategy	7	1,958	1,501
Nissan	▪ Showing firm wide big commitment ▪ BEV is the center of the strategy	7	6,609	552
PSA	▪ Overall EV strategy is still in shaping ▪ Will launch its own vehicles after 2013	8	3,156	340
Renault	▪ Showing firm wide big commitment ▪ BEV is the center of the strategy	9	17,144	2,246
Daimler	▪ Overall EV strategy is still in shaping ▪ Testing various suppliers and technologies	12	5,906	465
BMW	▪ Applying EV for small-size vehicles only	6	3,799	337
Chrysler	▪ Late in EV market ▪ Will launch its own vehicles after 2013	N/A	N/A	N/A
Hyundai	▪ ICE focused ▪ Fast following strategy	3	94	337

All major OEMs are pursuing xEVs, but with different strategic focus and development stages

Each OEM has different strategic commitment to xEV

SOURCE: Expert interviews, IIT, Literature search, Team analysis

Different grid applications require different technologies



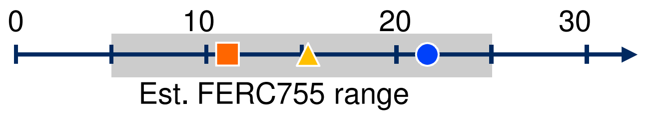
Source: ESA; team analysis

Based on projected costs, the battery opportunity is mainly in grid stability and lithium ion technology

Incumbent solution
2012
2020 projected
2020 breakthrough

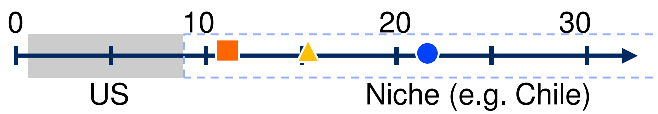
Technology | **Sample Application** | **Battery competitiveness[1]** | **Conclusion (2020)**

1a Lithium Ion | **Frequency regulation** | **LCOC[2]** $/MW-hr



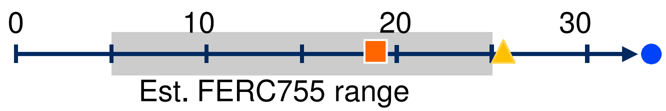
- Economic with anticipated rule FERC755; will continue to be attractive as costs decline

1b Lithium Ion | **Spinning reserves** | **LCOC** $/MW-hr



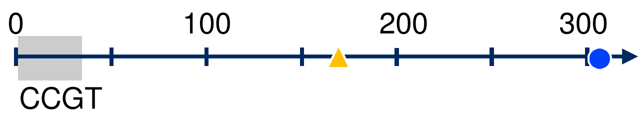
- Unlikely to be economic even with breakthroughs on cost curve (except in niche situations)

2 Fly-wheel | **Frequency regulation** | **LCOC** $/MW-hr



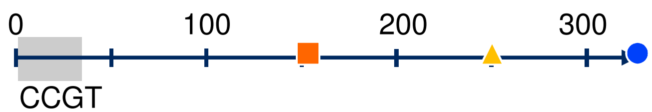
- May be economic but currently ~2x Li-ion installed cost

3 Advanced lead-acid[3] | **Bulk-time shift** | **LCOE** $/MWh



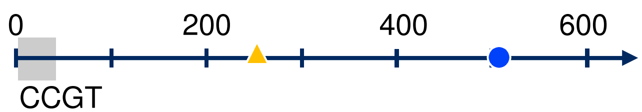
- Only economic in niche applications (e.g. burning petroleum at peak hours)

4 Molten Salt | **Bulk-time shift** | **LCOE** $/MWh



- Only economic in niche applications

5 Flow Cell[3] | **Bulk-time shift** | **LCOE** $/MWh

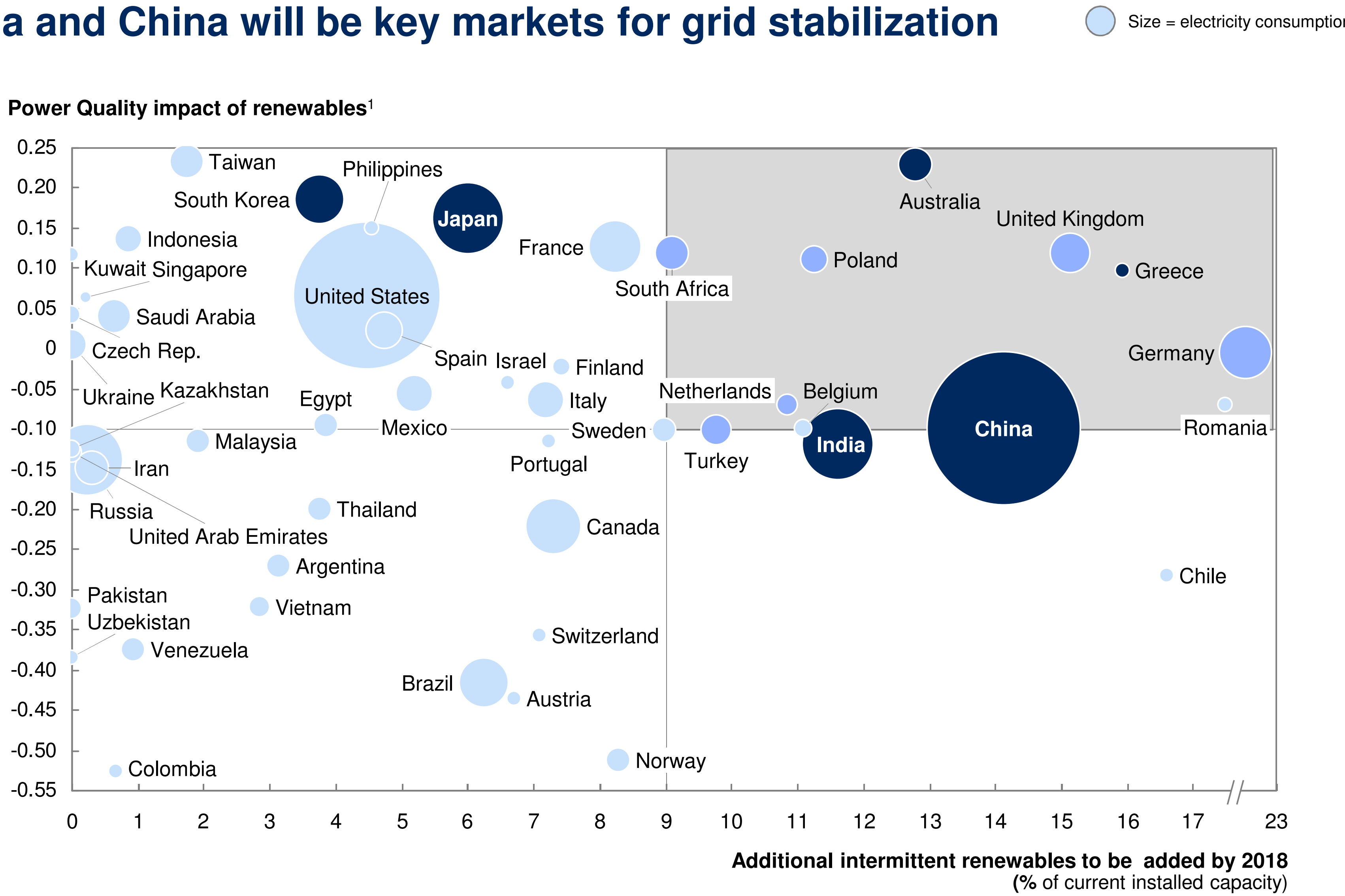


- Only economic in niche applications

1 Battery cost only – excludes energy cost
2 Levelized cost of capacity – based on current ISO data, upside for frequency regulation is based on pay for performance
3 Breakthrough scenario not identified as technologies are early. Bringing to commercial scale would be breakthrough

Source: Sandia 2013 Electricity storage handbook; McKinsey; National grid; Bundesnetzagentur; NRGY; REE; Energy Velocity

India and China will be key markets for grid stabilization



1 Higher impact relates to lower grid integration opportunities (few boundaries shared with other countries) and lack of hydro and natural gas generation