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LOCAL ENERGY, GLOBAL MARKETS
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Enovation Partners

Cost-Effective Decarbonization Pathways for Natural Gas

May 30, 2019

Energy + Innovation = Enovation

Founded in 2013 by energy leaders from top management consulting firms, Enovation was created with three goals:

1. **Drive innovation in energy and infrastructure**
   Help incumbents, investors, and early-stage companies navigate a changing industry
2. **Use an integrated approach to develop insights**
   Combine proprietary analytics and experienced consultants, developers, investors, and former executives with complementary perspectives and extensive networks
3. **Apply innovation to our own business:** Find new ways to deliver value to clients by addressing their specific needs through shared insights, and collaborative delivery of:
   - C-level consulting
   - Proprietary analytics, research, and data
   - High-visibility events and conferences

Our Business Units: Consulting, Analytics, Research, and Events

Enovation Partners

Enovation Analytics

Cleantech® Group

Consulting themes: DER/Storage, Gas Transition, Innovation

We focus on energy, accelerate innovation, and deliver results. In a word: Enovation

Gas Decarbonization Pathways – Phase 1 objective: Identify innovative gas end use technologies and translate their impact into customer value and environmental benefits

1 Innovation area

1	Condensing Technology
2	Hot water heating / boilers
3	Kitchen
4	On-Site Generation
5	Burners
6	Heat Pumps
7	Changes to laundry processing
8	Solar Thermal / Heat Recovery
9	Improved Energy Management
10	Transportation
11	Building Envelope
12	Miscellaneous

2 Technologies

1. Condensing Technology	Integrated contact condensing water heater
	In-situ flue burner - applying premix burners to storage GWH
	Transport Membrane Humidifier (TMH)
	High efficiency condensing condo packs
	Residential condensing water heater
	Condensing wall furnace
	Rooftop units - heating and cooling
	Condensing economizer
2. Boilers	Tankless water heater
	Solar-assisted heating
	Thermal compression gas heat pump
	Combined space and water heating systems

3 End-use pathways

4 Customer value

Affordability

Sustainability

Resilience

Comfort

12
Innovation areas

~100
Technologies

7
End use-pathways

26
Prioritized technologies

Note: Some technologies have multiple end uses and can be used in the residential and commercial sectors. These technologies are represented in all applicable sections

Wide range of sources from around the globe helped identify gas technologies that contribute to GHG reduction

Data Sources (partial list)

- Desk Research
  - ARPA-E
  - Canada Natural Gas Innovation Fund
  - Canadian Gas Association
  - Center for Climate and Energy Solutions
  - Gas Technology Institute (GTI) reports and Utilization Technology Department
  - Fraunhofer Institute
  - Korea Gas
  - Tokyo Gas
  - US DOE: NETL, NREL
- Personal communications
  - Engie
  - European Research Institute for Gas & Technology Innovation (ERIG)
  - Gas and Heat Institute (GWI - Germany)
  - Naturgy
  - GTI End-Use Department section leaders
  - Orsted
  - Osaka Gas
  - Other members of IGU Utilization Committee
  - UC Irvine
  - Westport Innovations
  - West River Capital

List of Technologies (examples)

- Condensing heat exchangers
- Condensing economizer
- Solar-assisted heating
- Tankless water heater
- High efficiency thermoelectric generators
- Enhanced radiant heat transfer
- Burner technology advancements (multiple)
- 3D printing for industrial burner design/production
- Advanced Gas Dryer Development
- Heat wheels for residential (air-to-air heat exchanger)
- Kitchen demand control ventilation
- Gas infrared drying
- Ozone laundry
- Liquid desiccant air conditioning/humidity control
- Gas Engine Heat Pump
- Gas fuel cell (multiple technologies)
- CHP : > 50kW and micro CHP (multiple technologies)
- Intelligent Energy Management (multiple)
- Hybrid homes (gas + electric)
- Zero Net Emission Home
- …

Extensive global research, interviews, workshops and conference sessions highlighted over 100 significant emerging gas technologies

Major End Uses and Representative Technologies

Technology Innovation Areas →

Residential

Building Energy Management 12
- Envelope
- IoT-based energy mgmt.

Water Heating 17
- Tankless water heater
- Gas heat-pump water heater

Cooking 1
- Gas oven and cooktop

Heating & Cooling 18
- Condensing furnace
- Heat pumps
- Solar thermal/ Heat recovery

Cogeneration/ Resilience 5
- Micro CHP
- Solid oxide fuel cells

Laundry 3
- Advanced gas dryer
- Ozone washing

Transportation 5
- Fuel Cell Electric Vehicle
- Home-refueling appliances

Commercial

Building Energy Management 10
- Demand controls for HW system

Water Heating 3
- Condensing economizer
- Grease Trap heat exchange

Cooking 6
- High production fryer
- Boilerless steamer

Heating & Cooling 13
- Heat pumps
- Condensing Condo Packs

Cogeneration/ Resilience 5
- Micro CHP
- Solid oxide fuel cells

Laundry 5
- Ozone washing
- Advanced gas infra-red burner

Transportation 9
- Commercial CNGVs
- Free-piston linear-motor compressor

→ Customer Value, GHG Impacts

Focus of the study

Outside of the main focus of the study

Notes: Total number of technologies exceeds 100 due to applicability to both sectors and multiple end uses

All technologies were first assessed against level of impact and time to market, as well as several other secondary criteria

Area	Assessment criteria
Energy and GHG Impacts	Impact on energy consumption (kWh/MMBtu)
	Impact on electric peak (kW) or gas peak (MMCFD)
	Overall efficiency improvement and GHG emissions reduction
	Accessible market size
Technology Maturity	Commercial availability < 5 years
	Commercial availability 5 to 10 years
	Commercial availability 10 to 15 years
Non-energy benefits	Effective use of waste heat
	Other factors – e.g., comfort; indoor air quality
Economics	Overall economics
	Susceptible to use of renewable gas
	Highly dependent on turnover of current stock
Regulatory/ Commercial Barriers	Technical barriers – relies on high GHG impact materials
	Practical barriers – space to install
	Safety
	Building codes
	Regulator-approved rebates
	LDC ability to market
Scale	Standardization of configuration
	Ease of scaling up to produce modules at scale

Comments

- Assessment framework helped prioritize gas technologies based on relative level of impact and market readiness
- Additional research gathered data to serve as foundation for:
  - Estimating energy savings and emissions impact at technology level
  - Incorporating into relevant end use pathways
  - Estimating energy savings and emissions impact at customer and pathway levels
  - Mapping economics and barriers into expected market penetration rates

Innovative technologies were assessed, prioritized and aligned with relevant end use pathways

High priority technologies by major end use

- Low-cost residential gas absorption heat pump (GAHP) combination
- Condensing furnace
- Transport Membrane Humidifier (TMH)

- Tankless water heater - Maintenance-free approaches for tankless water heaters
- Solar-assisted heating - PV assisted domestic hot water heater (potable)
- Unplugged power burners - Two-Phase Thermo-Syphoning (TPTS) technology
- Combined Space and Water Heating Systems*

- Ozone and cold water washing

- High production fryers
- Multistacked boilerless steamer for high volume cooking
- Combination steam and heat oven

- IoT thermostats (i.e. Nest, Honeywell)
- Building envelope (insulation, windows, building materials)
- Demand controls for HW systems
- Thermostatically controlled low flow shower head

- Solid oxide fuel cells*
- Micro CHP – gas recip, sterling engine*

- Fuel cell electric vehicles (hydrogen)
- Commercial CNG vehicles

Note: All technologies were independently evaluated and scored by several SMEs; evaluation criteria primarily considered GHG impact and time to market; aggregated scores were consistent among experts and robust against multiple weightings; * designates technology with multiple end-uses, but listed only once

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Combining emerging end-use technologies in the residential sector creates multiple pathways for customers to reduce GHG

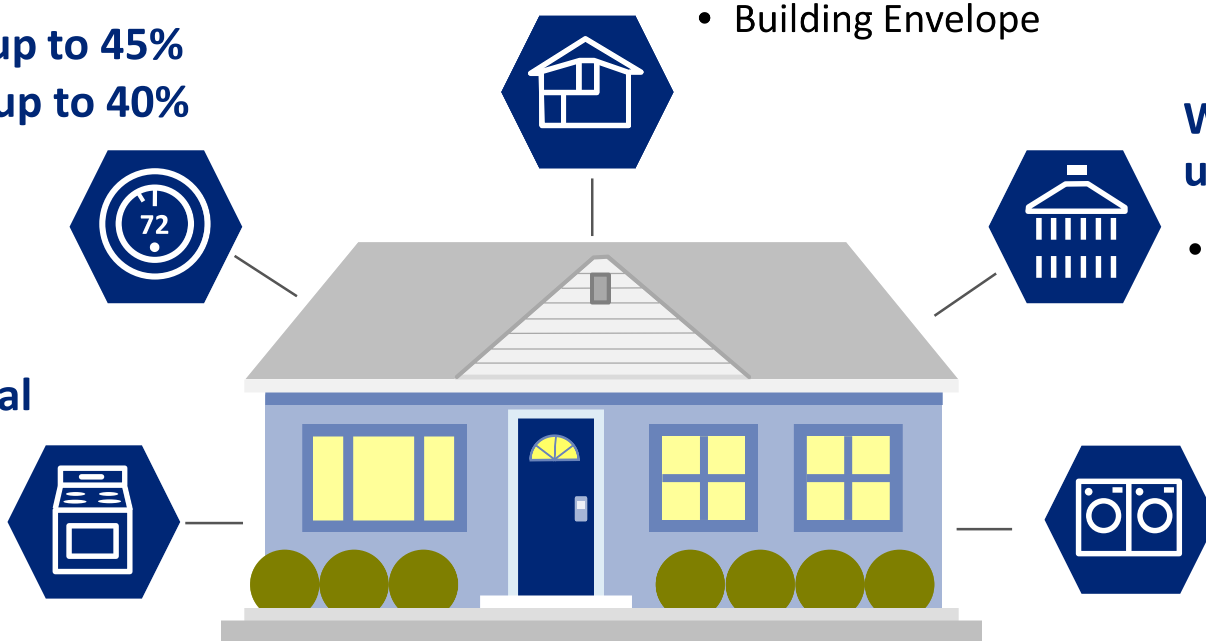
Building Efficiency, 10-45%
- IoT based thermostat
- Building Envelope

Space Cooling, up to 45%
Space Heating, up to 40%
- Gas heat pump

Water heating, up to 55%
- Absorption heat pump

Cooking, minimal change
- Gas stove
- Gas oven

Laundry, 55%
- Gas dryer
- Ozone washing



Notes: GHG reduction potential is estimated based on efficiency improvements over stock average gas equipment efficiency in 2016

Combining emerging end-use technologies in the commercial sector creates multiple pathways for customers to reduce GHG

Energy Management & Building Efficiency, 10-45%
- Building Envelope
- IOT Thermostat

Cooking, up to 40%
- High efficiency fryer

Water heating, up to 15%
- Condensing storage

Transportation, up to 20%
- Commercial compressed natural gas vehicles

Electric Generation, Space Heating, up to 50%
- CHP, Gas Recip Engine

Notes: GHG reduction potential is estimated based on efficiency improvements over stock average gas equipment efficiency in 2016

Emerging gas technologies can make substantial and cost-effective contributions to GHG reduction goals

~100

Innovative Gas Technologies for Residential / Small Commercial identified in our global search

25-40%

GHG reduction potential on a customer basis by integration of these technologies and other efficiency practices

60-80%

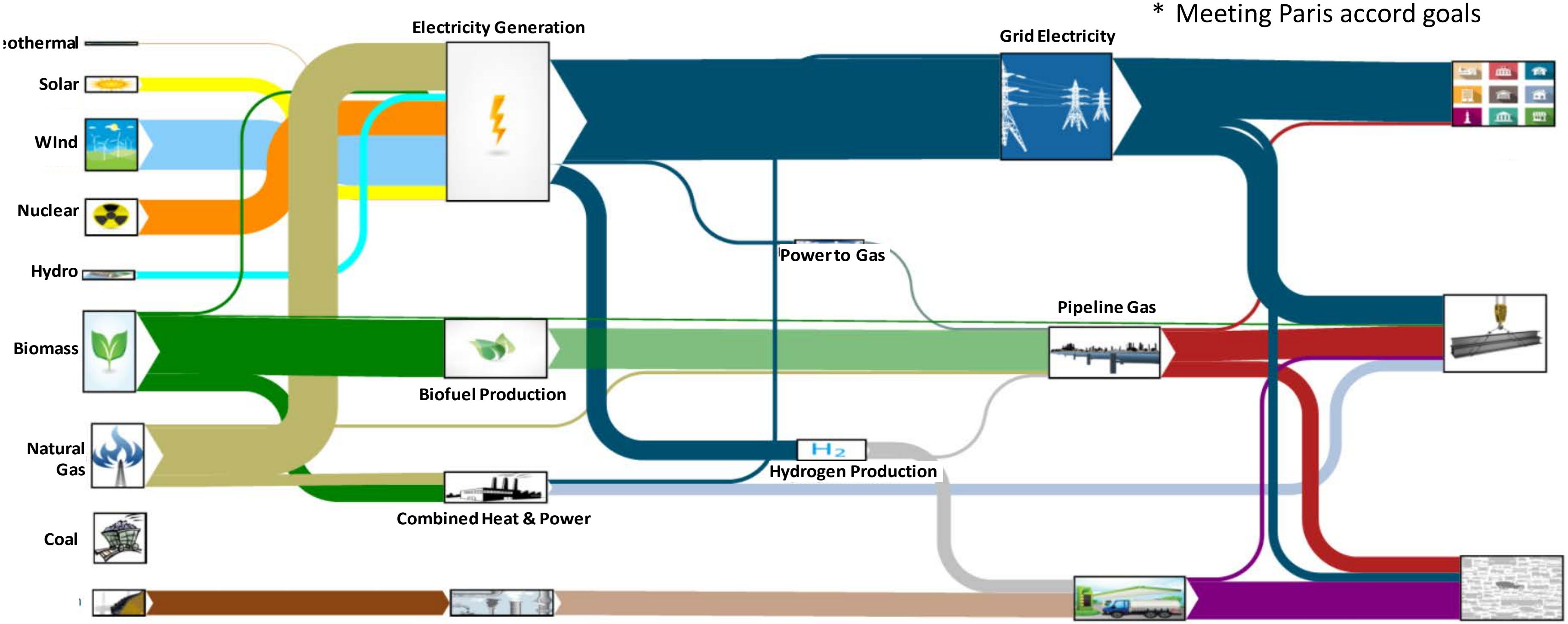
GHG reduction – sufficient to meet COP 21 goals – with inclusion of future CHP technologies and Renewable Gas

- Policy goals for sustainable energy can be achieved at significantly lower consumer cost through integrating innovative gas solutions.
- Gas technologies can enhance energy system reliability (system-wide and as a local backup) and efficiency, while reducing the need for new electric generation and T&D infrastructure and preserving the future value of gas infrastructure.
- Electric technologies will also improve, and are supported by incentives, but their GHG impacts depend on the generation fuel mix. In some regions electrification will increase GHG emissions through the 2030s.

Mixed pathways show larger generation role for natural gas; renewable gas for industry/transport

Sankey diagram for U.S. energy system in 2050* – Mixed Case

* Meeting Paris accord goals



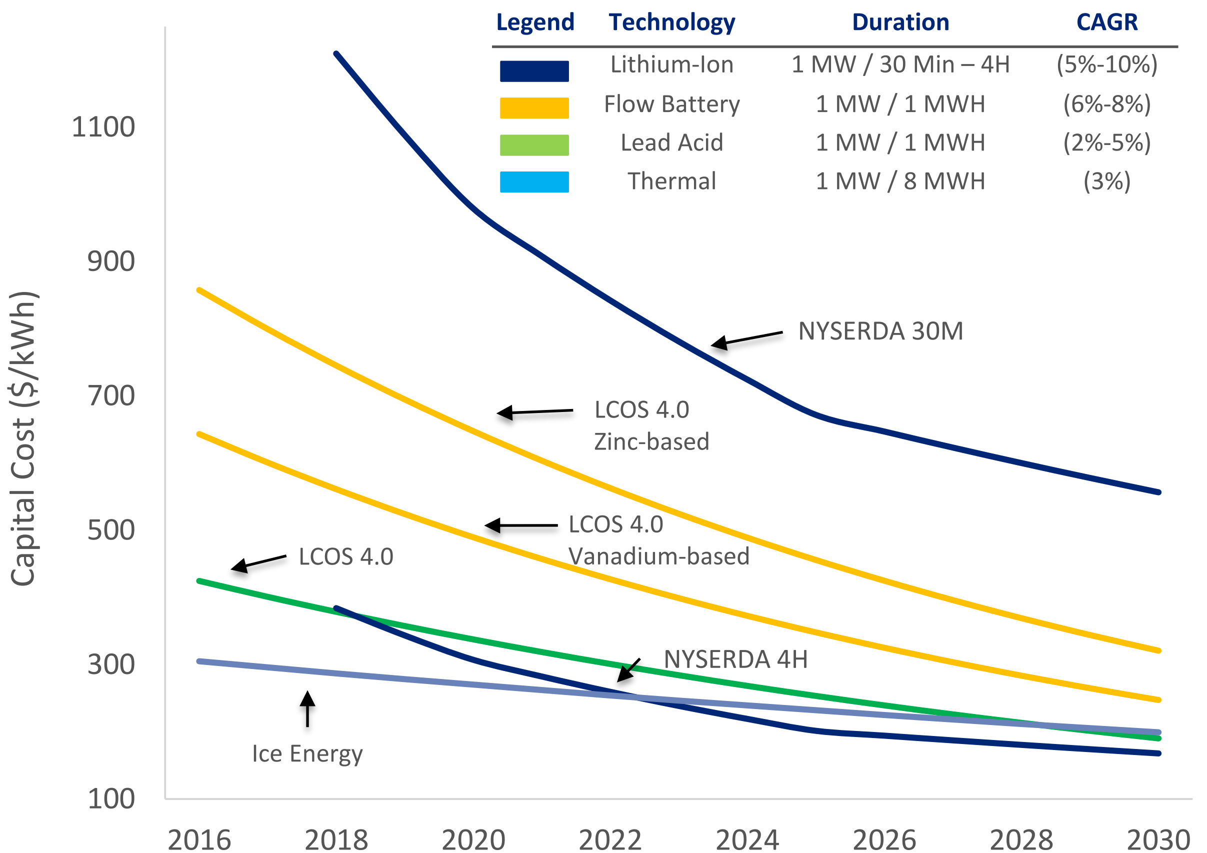
Source: Deep Decarbonization Pathways Project, 2015

- Mid-range assumptions on renewable electricity build-out; lower surplus for PTG and hydrogen production
- Gas for industry/transport is almost all renewable gas. Hydrogen plays larger role in transportation. Industrial gas consumption only modestly lower.
- Mixed case substantially lower cost than High Renewables case in most scenarios

Electricity storage will be key enabler for deeper penetration of renewables – storage systems costs will halve over next decade

Overnight Cost of Energy Storage System

($2016)

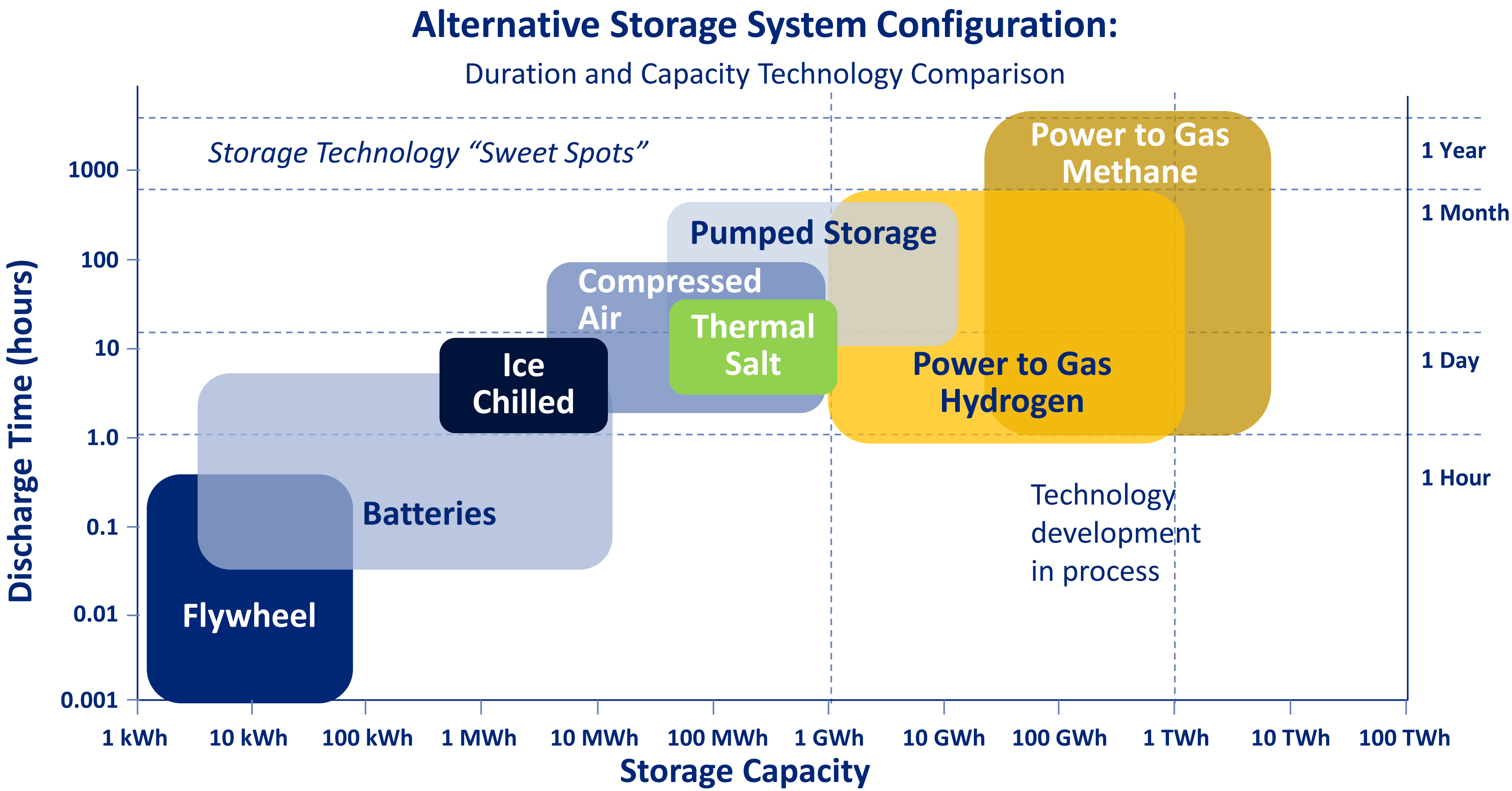


Sources of Progress

- **Lithium-Ion:** Manufacturing scale and performance improvement will be key drivers of cost declines:
  - Energy densities of Li-Ion cells have improved by ~110% between 1996 and 2016, from ~110 to ~230Wh/kg
  - Commercialization of new Li-Ion chemistries (e.g. Li-Air, Li-S) and performance (e.g. voltage, anode capacity)
- **Flow Battery:** Substitution of high cost transition metal elements (vanadium), for lower cost synthetic materials that can be sourced from existing chemicals already widely used in industry
- **Lead Acid:** Mature technology (e.g. car batteries) with limited ability to materially reduce cost
- **Ice Energy:** Mature technology (20+ years-old) with limited ability to materially reduce cost

Source: BNEF, IRENA, NYSERDA, Lazard, Enovation Partners analysis
Flow Battery, Lead Acid installed costs calculated using BNEF BOS data, where appropriate. *Ice thermal energy based on reported project cost in Sandia. Costs are AC and include EPC. Land not included.

Gas could play an important role in large-scale, long-duration storage of renewable energy – not good application for batteries



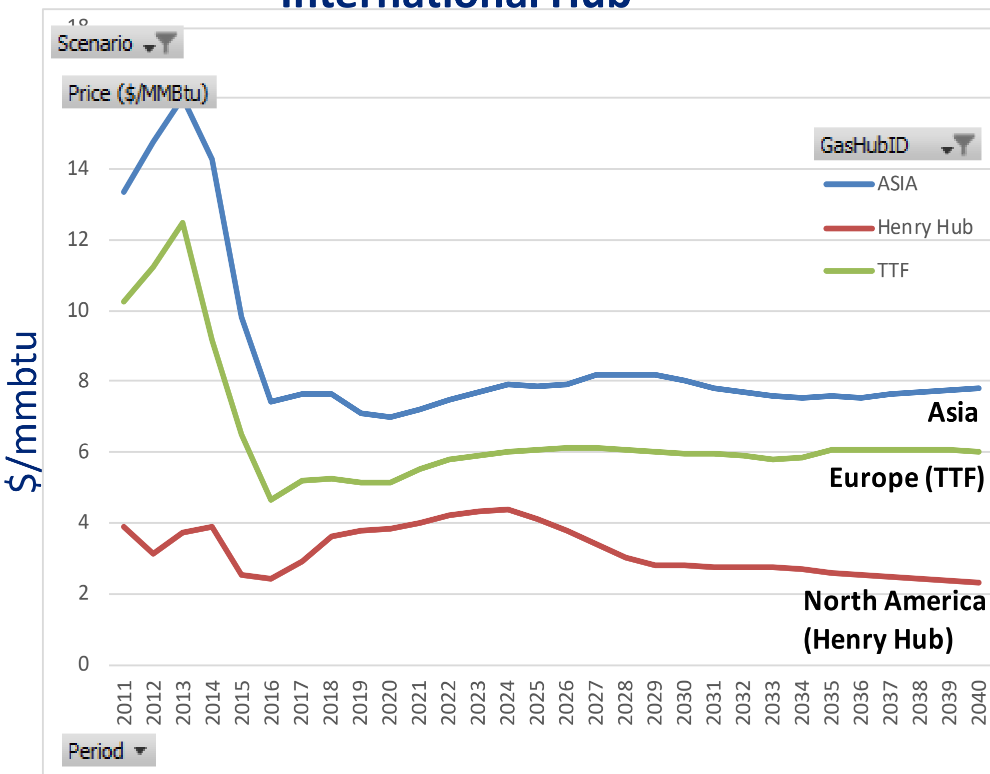
- Using gas cycles for storage of large amounts of surplus renewables
- Potential long-term repurposing of gas infrastructure
- PTG scale-up needs large cost reductions or strong policy support

Source: Enovation Partners, California Hydrogen Business Council

How would accelerated renewables development in Europe and North America affect global gas markets?

Delivered Real Prices by International Hub

(Analysis conducted for World Gas Conference 2018)



- Constructed Minimum Gas scenario through 2040
- Assumed further decarbonization of electricity sector and accelerated decarbonization of transport sector, beyond Sustainable Policies case.
- These trends were assumed to affect Europe and North America first, then middle-income countries (notably China, India and Brazil) on roughly a five-year lag.
- Modeled impact with **RBAC's G2M2® Global Gas Market Modelling System**. Detailed supply, transport and cost logic by major production region.

Results:

- Gas demand drops in Europe & North America. Lower LNG prices spur higher demand growth in developing countries.
- Backing down the supply curve, North American LNG pushes out much production from other mid-cost production regions. U.S. becomes largest LNG exporter. Global natural gas demands decline modestly.

Source: RBAC, Inc.; Enovation Partners analysis

Surprisingly broad areas of electric and gas utility consensus on decarbonization policy principles

- Think of the energy system as a whole — all sectors. Don't ignore infrastructure costs.
- Involve customers or their representatives in the debate about decarbonization strategies.
- Remember that costs and affordability are very important to customers. Pricing and rate structures are a tool/problem.
- We need durable policies to be able to attract investment into lower-carbon solutions.
- Pathways should be technology-agnostic. Leave room for innovation and future flexibility to leverage technology advancements.
- Mandates are much less effective and costlier than targets with compliance flexibility.
- A balanced, broad approach is best. Nobody advocated for electrifying everything.
- Biggest challenge in regions with high renewables penetration is decarbonizing transportation. The grid is getting cleaner quickly.
- Solutions should be scalable and exportable for an effective global effort.
- Achieving the right policy solution will be difficult, but that's not an excuse for inaction.

Source: Panel discussion on "Best Decarbonization Pathways for Customers" at Western Energy Institute board meeting, January 2019

Further Research

- Kicking off Phase 2 of Pathways project in June 2019
  - Funded by American Gas Foundation (public interest/educational affiliate of American Gas Association)
  - Update inventory and commercial status of emerging gas end use technologies
  - Analyze equipment investment economics from customer perspective
  - Develop market penetration scenarios through 2040; identify key policy levers
  - Compare GHG abatement costs with alternative decarbonization pathways

- Support development of renewable natural gas (RNG) technologies and business models
  - Biogas pathways
  - Power-to-gas cycles
  - Many hydrogen projects under development in Europe and North America
  - Analysis of policy support requirements (subsidies, carbon prices)

Energy + Innovation = Results

Bill Kemp

wkemp@enovationpartners.com

+1-041-448-5674