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U.S. DOE carbon capture program: Advancing multiple generations of carbon capture solutions laboratory to pilot scale development

Jose Figueroa
U.S. Department of Energy National Energy Technology Laboratory, jose.figueroa@netl.doe.gov

Driving Innovation ♦ Delivering Results







U.S. DOE Carbon Capture Program:

Advancing Multiple Generations of Carbon Capture Solutions

Laboratory to Pilot-Scale Development

José D. Figueroa
Carbon Capture Coordinator - Capture Division
National Energy Technology Laboratory

Presentation Overview

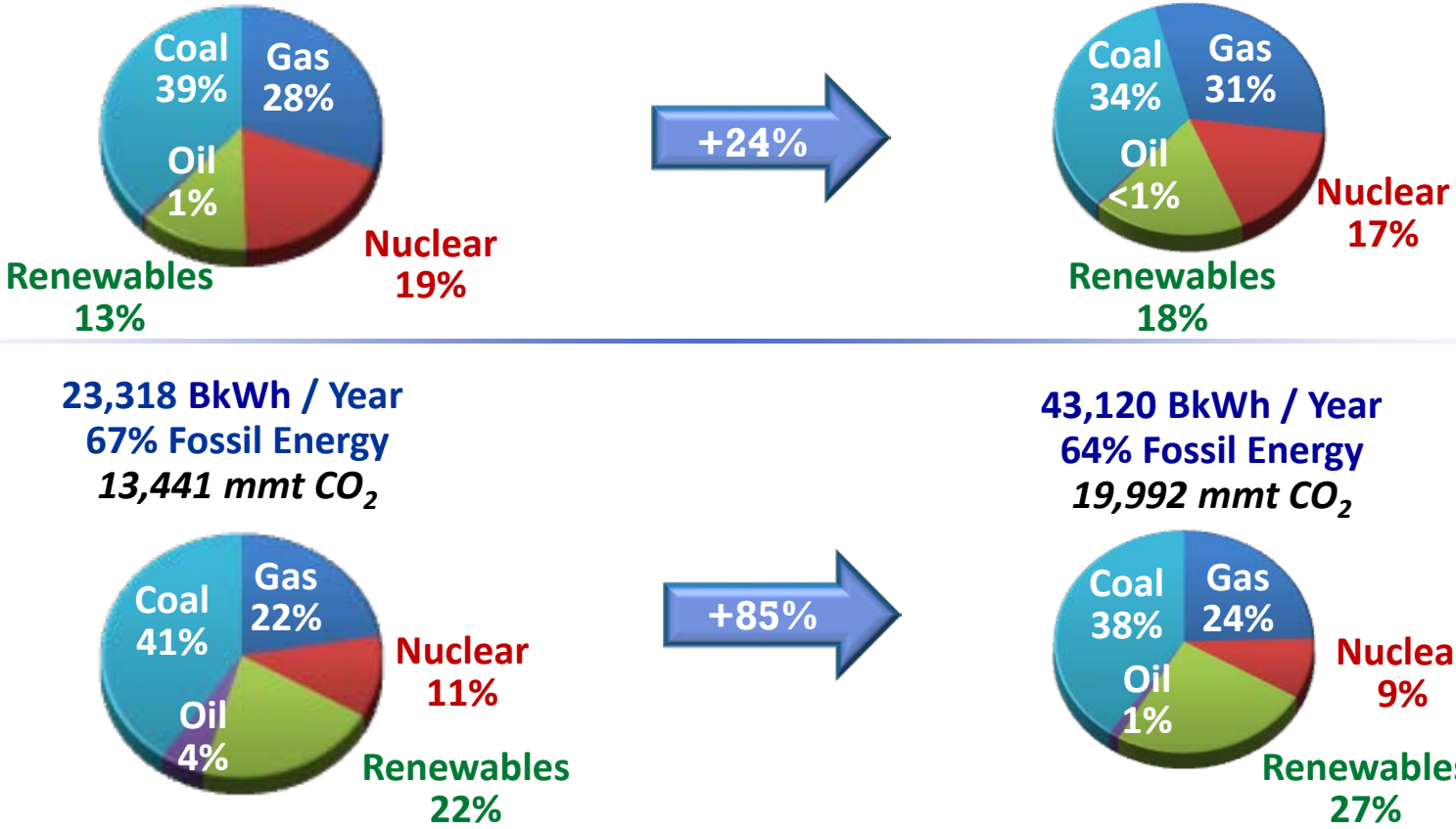
- **Challenges to GHG Abatement Exist**

- **Successful implementation of GHG abatement strategies requires:**
  - Public/Private Partnerships
  - Efficient utilization of resources for an existing and growing CCS market

- **Prospective 2nd Generation technologies are moving to pilot scale, but require market-based support**
  - The search continues for a suite of economically sustainable solutions

U.S. and World Electricity Generation

	2013	2040
United States	4,049 BkWh / Year 68% Fossil Energy *2,053 mmt CO_2*	5,031 BkWh / Year 65% Fossil Energy *2,195 mmt CO_2*
World	23,318 BkWh / Year 67% Fossil Energy *13,441 mmt CO_2*	43,120 BkWh / Year 64% Fossil Energy *19,992 mmt CO_2*



U.S. data from EIA, Annual Energy Outlook 2015; World data from IEA, World Energy Outlook 2015, Current Policies Scenario

Capture Program Development Path

Performance Improvement & Scale Up Drive Costs Down

Laboratory- & Bench-Scale

- Simulated operating conditions
-Short duration tests (hours/days)
- Proof-of-concept and parametric testing
- High risk

TRL: 2-4

Small & Large Pilot-Scale Slipstream

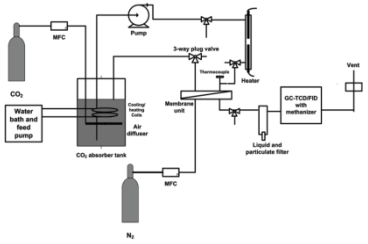
- Real operating conditions
- Longer duration tests (weeks/months)
- Lower risk

TRL: 5-7

Demonstration-Scale

- Variable operating conditions
- Extended duration (typically years)
- Demonstrate integrated full-scale; Minimal risk commercial application
- CO_2 Utilization/Storage

TRL: 7+



1 MW Membrane Pilot (MTR)

5 MW Oxy-combustion Pilot (Alstom)

25 MW Solvent Heat Integration (Southern Company)

Then (>$100/Tonne) → ***Now (~$60/Tonne)*** → ***Future (<$40/Tonne)***

R&D Areas: CO_2 Capture

Pre-Combustion

- ❑ *Solvents*
- ❑ *Sorbents*
- ❑ *Membranes*
- ❑ *Novel Concepts*

1st-Generation Technologies—*include technology components that are being demonstrated or that are commercially available.*

2nd-Generation Technologies—technologies currently in R&D scheduled to complete large-scale pilot testing by 2020 and complete demonstration scale testing by 2025.

Transformational Technologies—*emerging technologies in early stages of development that offer the potential for "game-changing" improvements in cost and performance scheduled to complete large-scale pilot testing by 2025 and complete demonstration scale testing by 2030.*

Post-Combustion

- ❑ *Solvents*
- ❑ *Sorbents*
- ❑ *Membranes*
- ❑ *Novel Concepts*

Post-Combustion Research Focus

Key Technologies	Research Focus
Solvents	• Low-Cost, Non-Corrosive Solvents with High CO_2 Loading Kinetics, Low Capacity, Improved Reaction Regeneration Energy, and Degradation Resistance • Process Intensification/Heat integration • **High Performance Functionalized Solvents** • **Catalyzed Absorption** • **Phase-Change Solvents** • **Hybrid Systems** • **Cryogenic Capture**
Sorbents	• Low-Cost Base Materials, Thermal and Chemical Stability, Low Attrition Rates, Low Heat Capacity, High CO_2 Adsorption Capacity and High CO_2 Selectivity • Process Intensification/Heat integration • Novel Processes Equipment and Configurations • **Structured Solid Adsorbents (eg., MOFs)** • **Hybrid Systems** • **Enhanced PSA/TSA**
Membranes	• Low-Cost, Durable Membranes with Improved Permeance, Selectivity, Thermal and Physical Stability, and Tolerance to Flue Gas Contaminants • **Hybrid systems** • **Novel Process Conditions** • **Nano-materials**
Novel Concepts	• Supersonic Shockwave CO_2 Compression • **Hybrid Systems** • **Cryogenic Capture**

• **2nd Generation Technology** • **Transformational Technology**

Pre-Combustion Research Focus

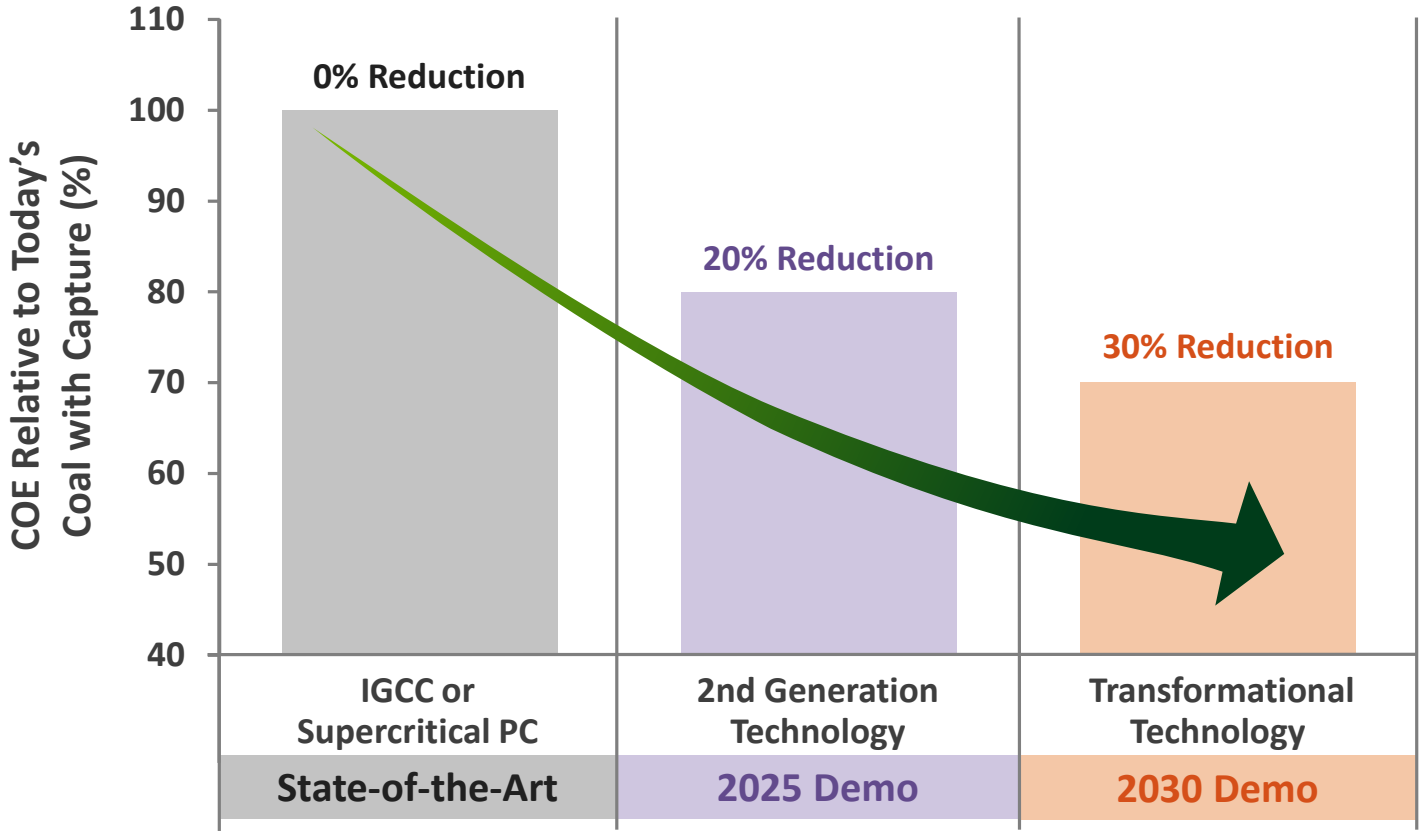
Key Technologies	Research Focus
Solvents	• Advanced Regeneration Process to Produce a High-Pressure CO_2 Stream • Increased Selectivity for Maximal H_2 Recovery • High temperature operation to maintain warm syngas • **Dual Swing Absorption/Regeneration Cycles** • **Hybrid Systems**
Sorbents	• Cyclic PSA Producing High-Pressure H_2 and CO_2 • **WGS/CO_2 Separation Process intensification for High Efficiency Impact** • **Hybrid Systems**
Membranes	• Membrane Materials: High-Temperature Polymer, Dual-Phase Carbonate-Ceramic, Pd, and others • Silica Molecular Sieve • Gas/Liquid Contactor • **WGS/CO_2 Separation Process intensification for High Efficiency Impact** • **High Density and Pressure Nano-Scale Membranes** • **High-temperature/high-pressure seals** • **Process Intensification** • **Hybrid Systems**
Novel Concepts	• **WGS/CO_2 Separation Process intensification for High Efficiency Impact** • **Hybrid Systems**

• **2nd Generation Technology** • **Transformational Technology**

Program Goals

Driving Down the Cost of Electricity of Coal Power with CCS

Cost of Electricity Reduction Targets



Goals are for greenfield plants. Costs include compression to 2215 psia, but exclude CO_2 transport and storage costs.

Capture Program: Active Portfolio Distribution

Program Area	Key Technology	Number of R&D Projects			Total	
		Lab/Bench	Small Pilot	Large Pilot		
Post-Combustion Capture	*Solvents*	10	4	6	**20**	39
	Sorbents	5	2	-	**7**	
	Membranes	5	2	-	**7**	
	Novel Concepts	4	1		**5**	
Pre-Combustion Capture	*Solvents*	-	1	-	**1**	9
	Sorbents	-	1	-	**1**	
	Membranes	5	-	-	**5**	
	Novel Concepts	2			**2**	
Compression	*Compression*	-	-	1	**1**	
Totals		**31**	**11**	**7**	**49**	

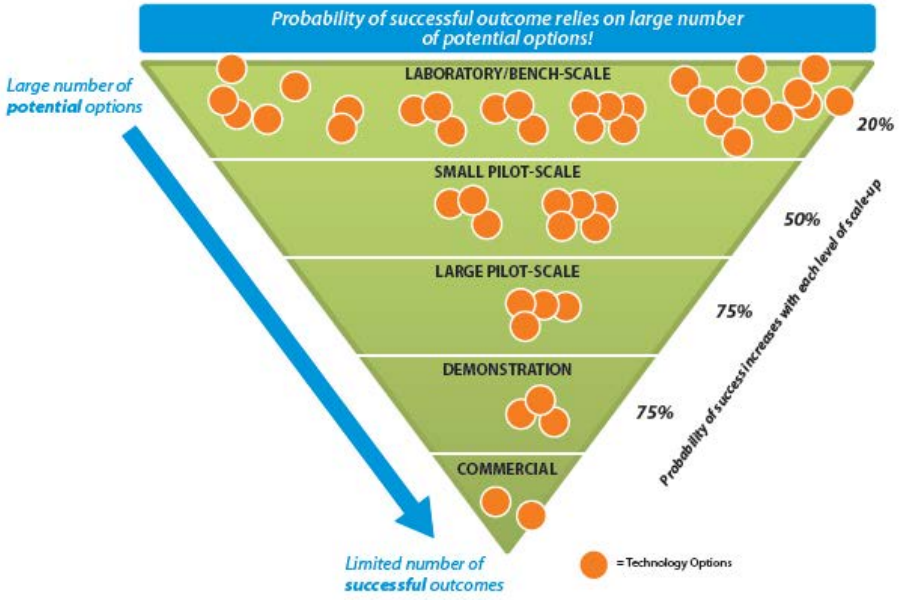
Note:
1. 6 large scale pilot projects will undergo a down-selection for Phase 2 in 2016
2. Number of projects in portfolio changes over time.

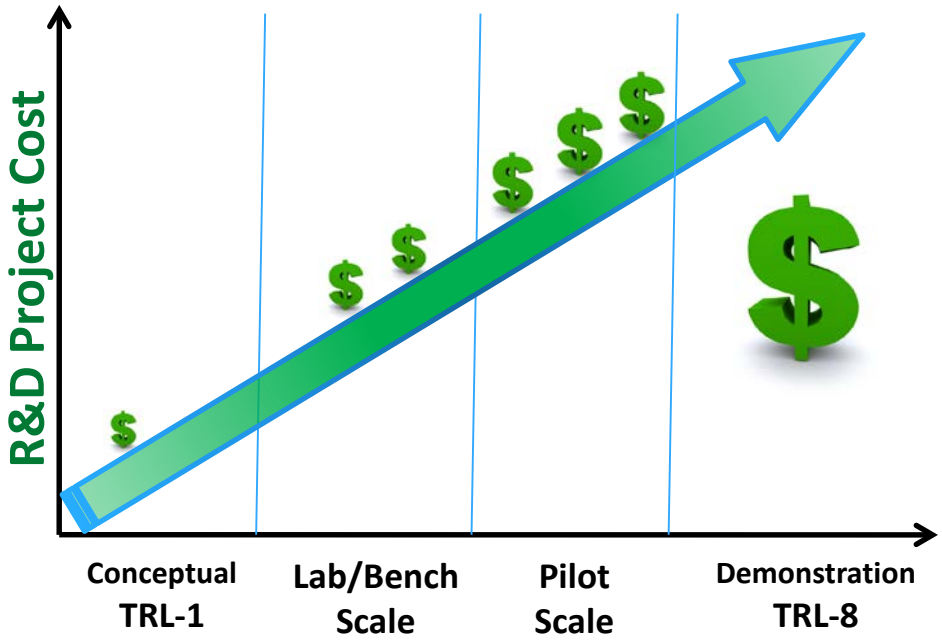
Looking Forward

- **2nd Generation:** Increased Focus on Pilot-Scale
- **Transformational:** Development at Laboratory/Bench Scale

Laboratory / Bench-Scale

PNNL - Pacific Northwest National Laboratory
CO2-Binding Organic Liquid (CO2BOL) Solvents





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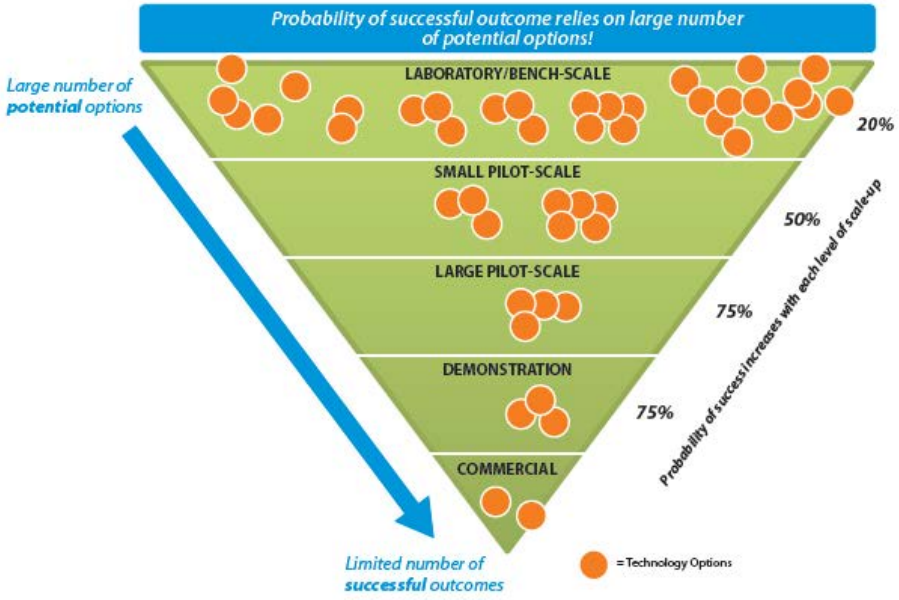
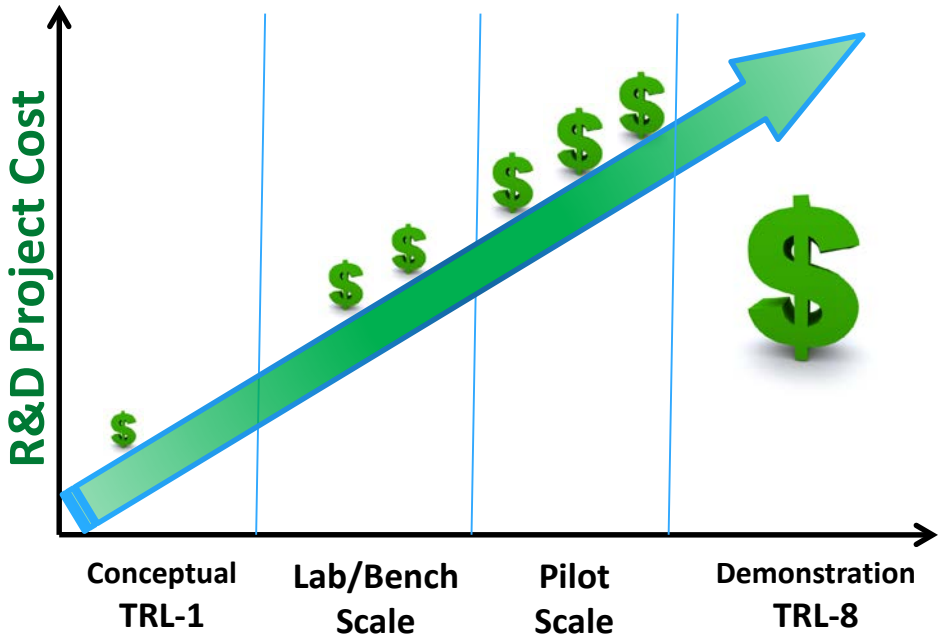
Laboratory / Bench-Scale

LLNL - Lawrence Livermore National Laboratory
Enhanced Manufacturing of Solvents





Looking Forward

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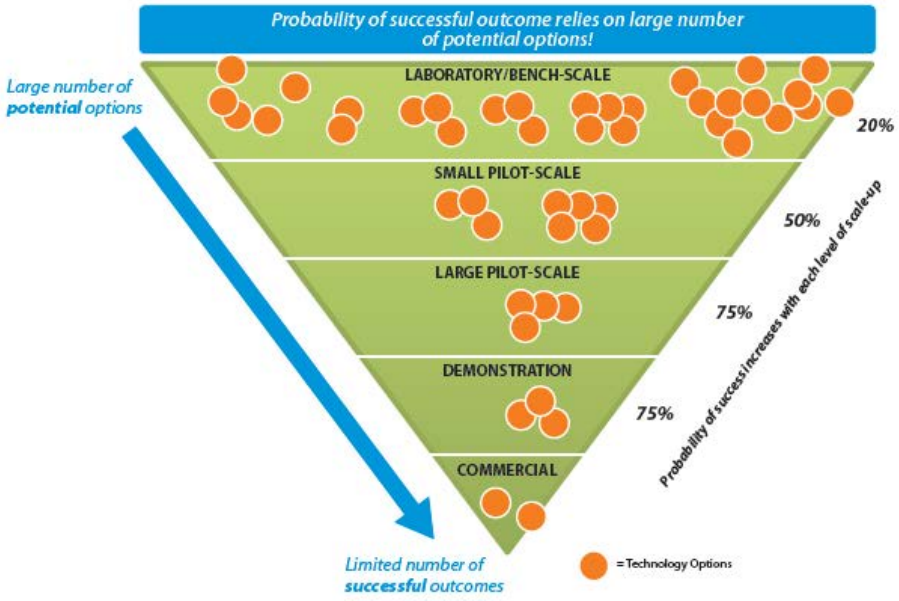
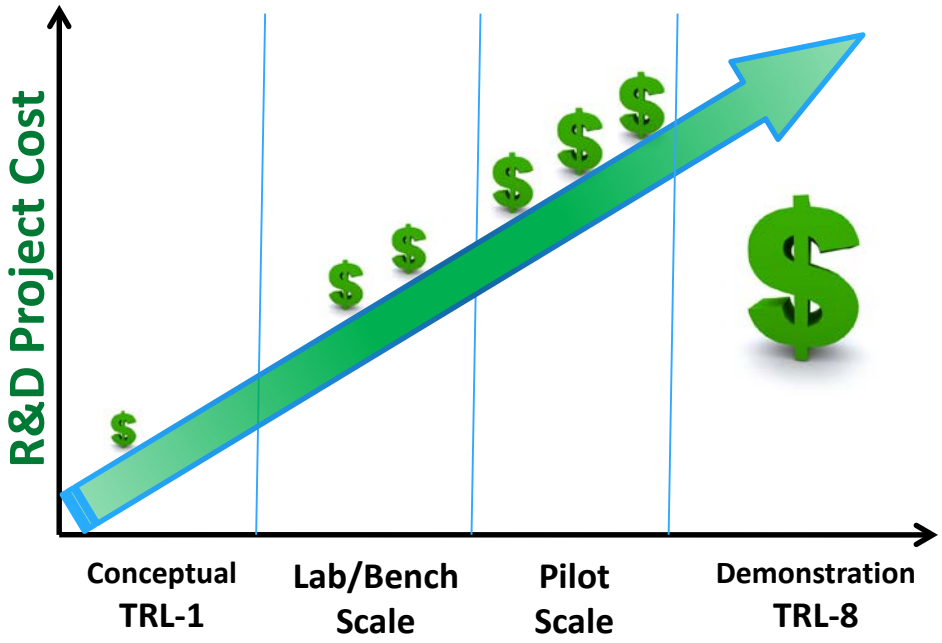
Laboratory / Bench-Scale

University of Notre Dame
Encapsulated Ionic Liquids





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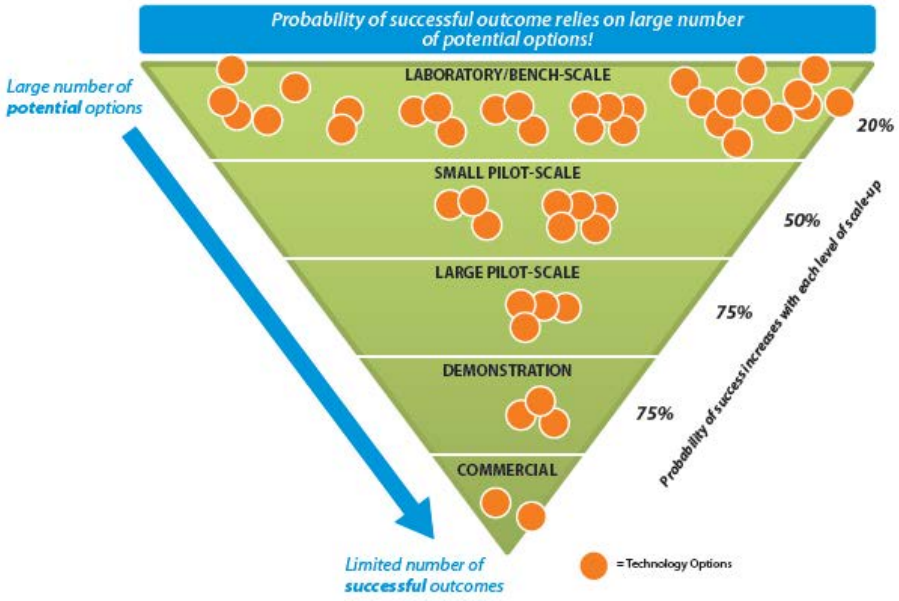
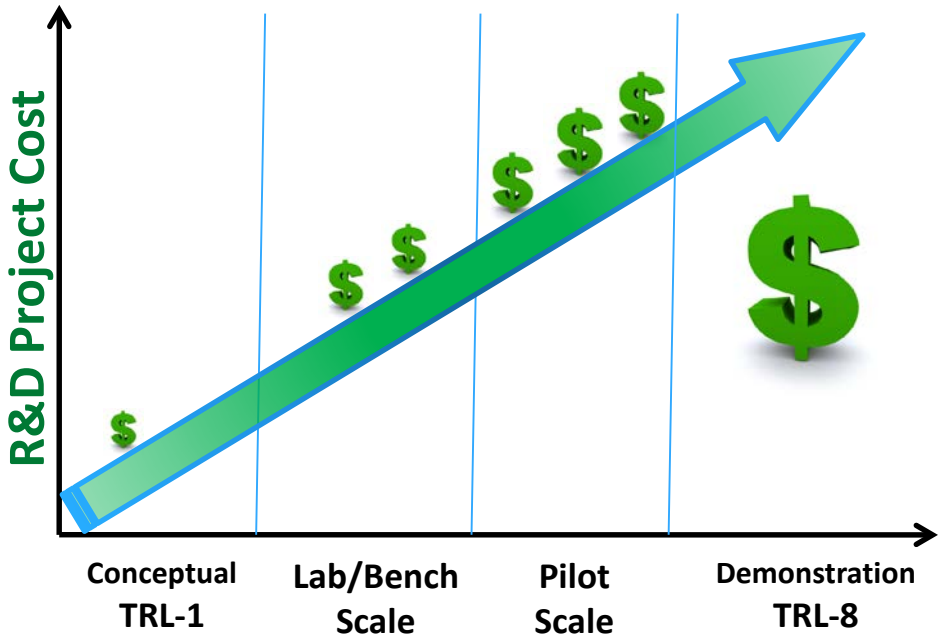
Laboratory / Bench-Scale

University of Illinois
Biphasic Absorption with Phase Separation





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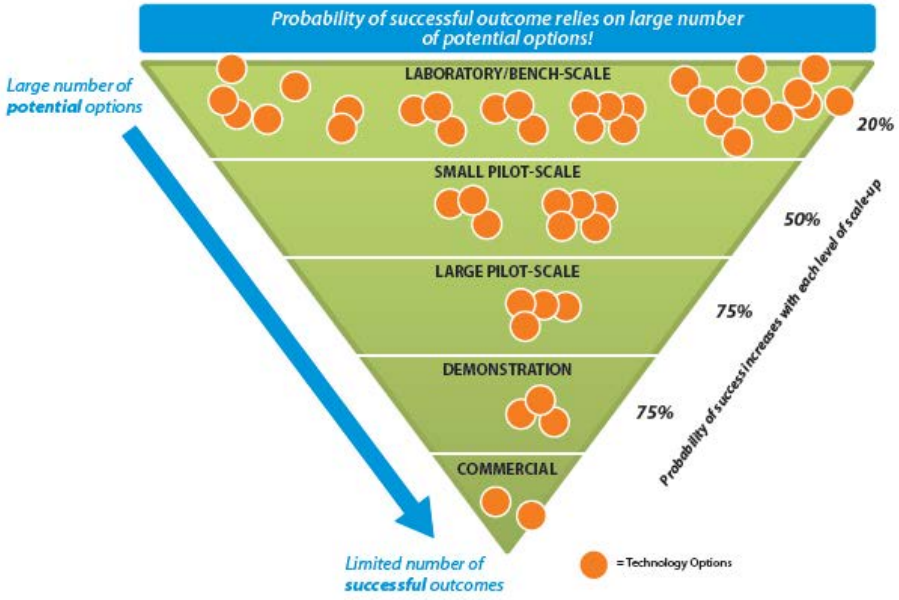
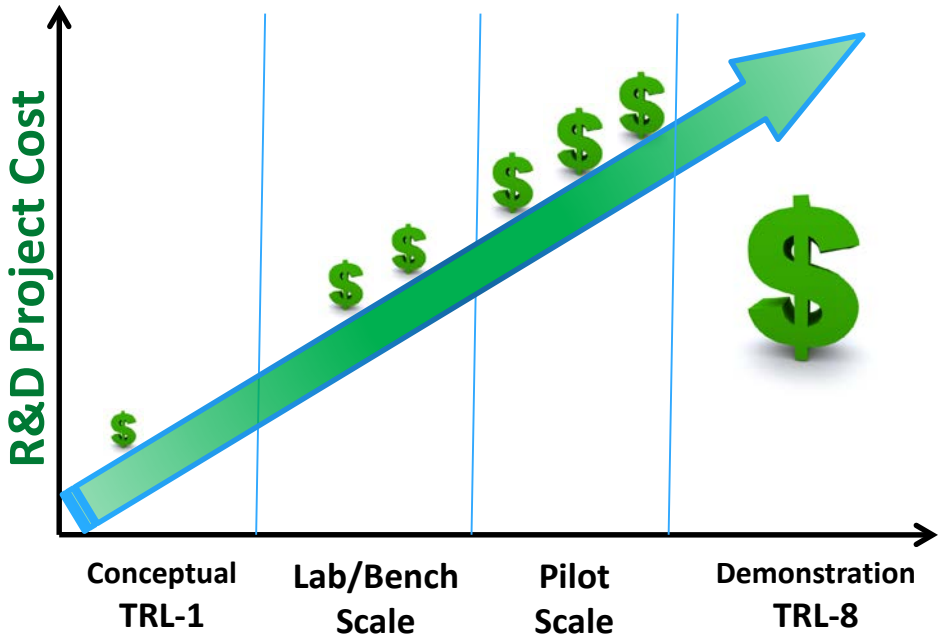
Laboratory / Bench-Scale

Texas A&M University
Amine-Incorporated Porous Polymer Networks (APPNS)





Looking Forward

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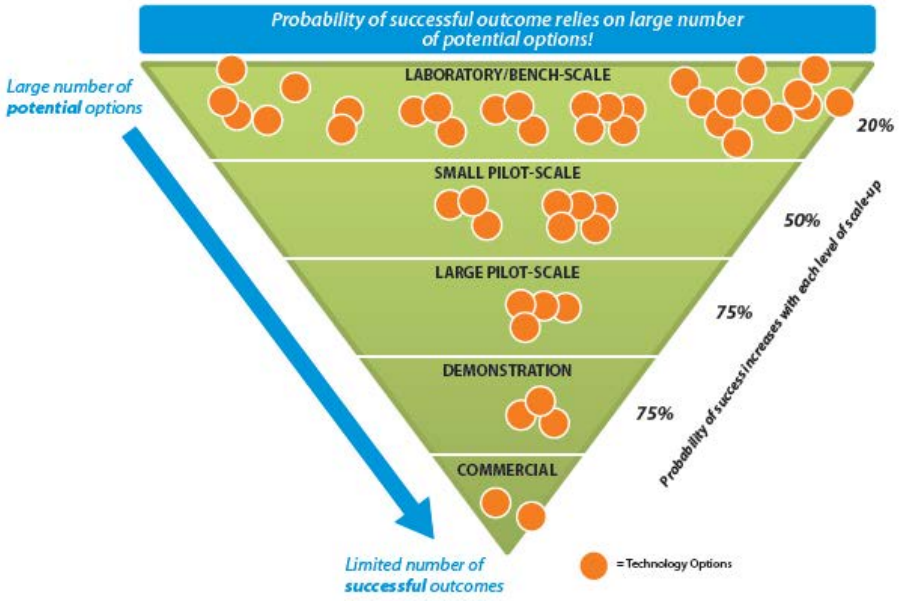
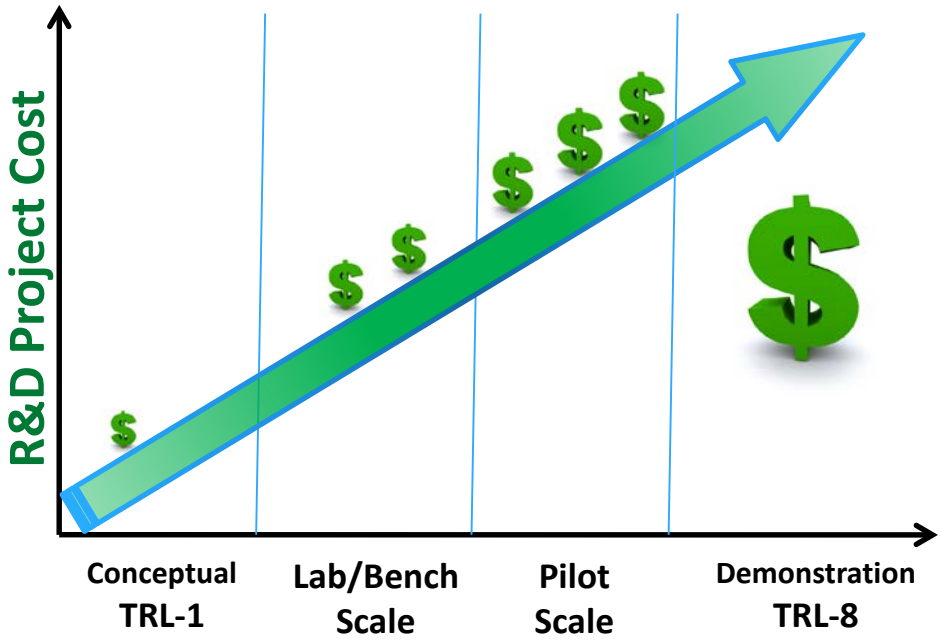
Laboratory / Bench-Scale

Georgia Tech Research Corporation
Novel Rapidly Cycled Pressure Swing Adsorption Process





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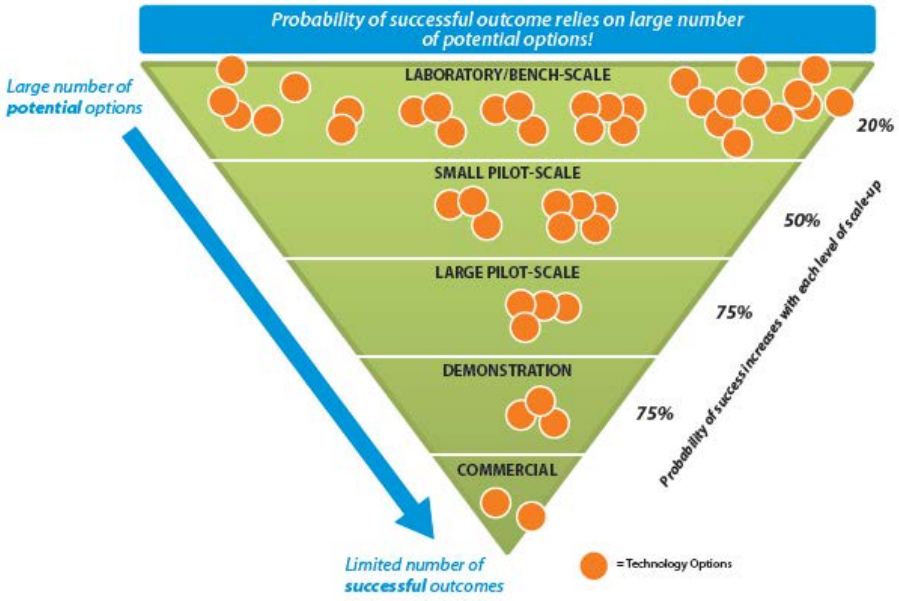
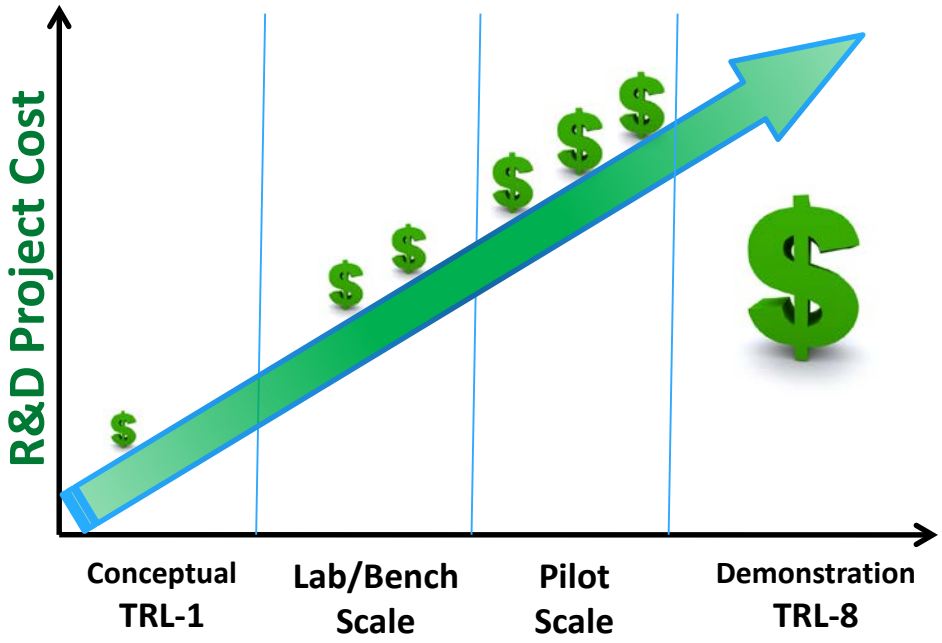
Laboratory / Bench-Scale

Research Triangle Institute
Novel Hybrid Fluidizable Sorbents





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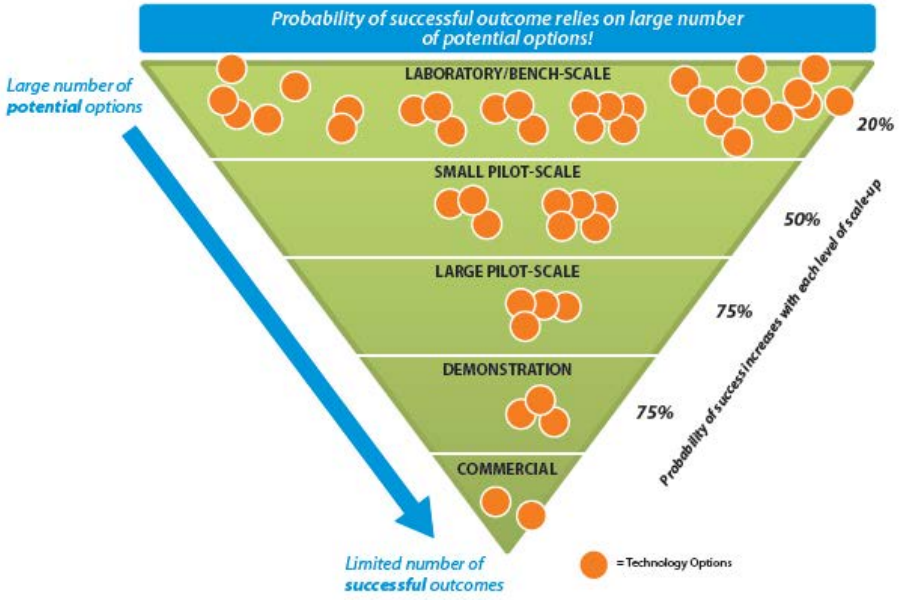
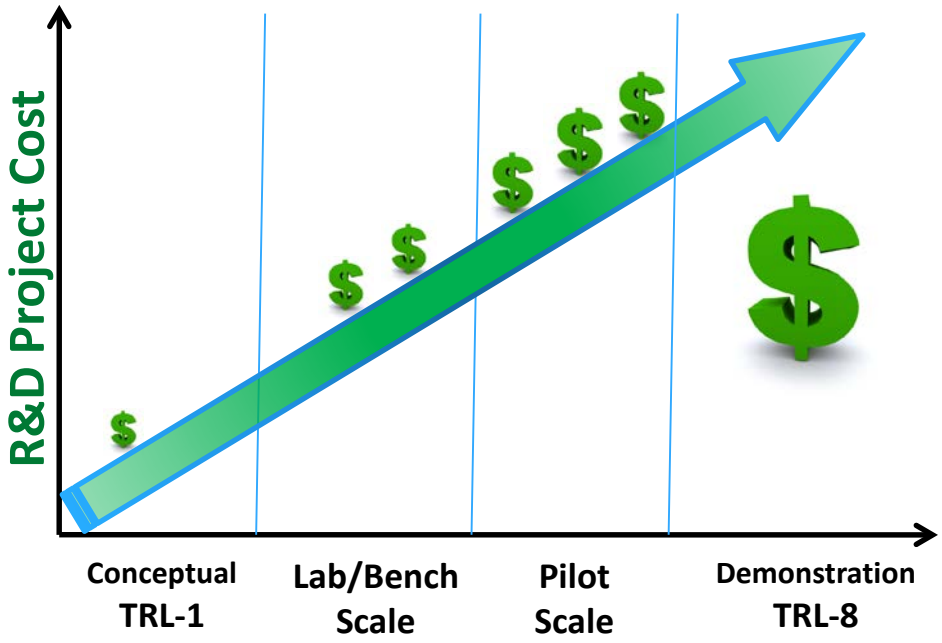
Laboratory / Bench-Scale

Gas Technology Institute
Go-Peek Hybrid Membranes





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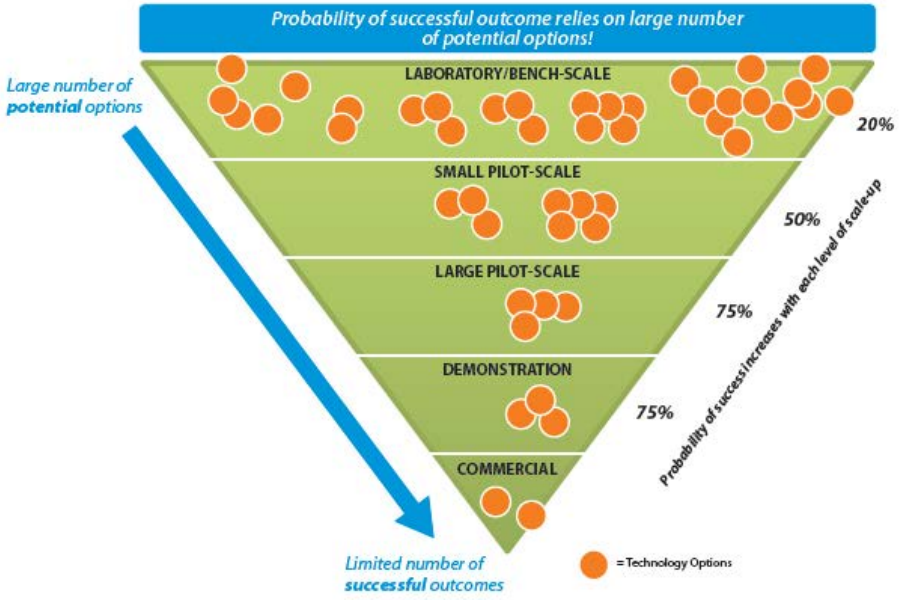
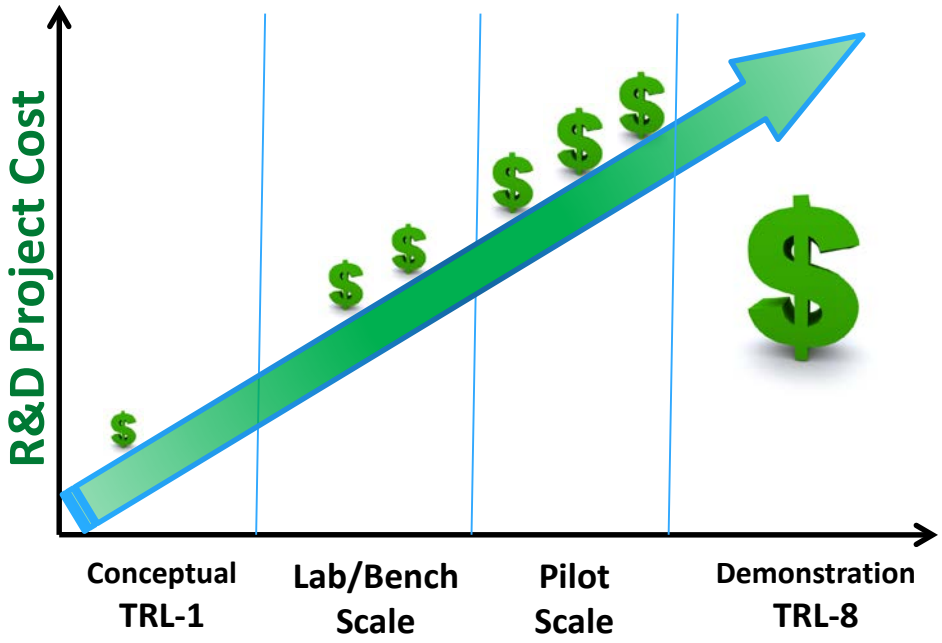
Laboratory / Bench-Scale

Liquid Ion Solutions LLC - Hybrid Advanced Membrane, Solvent System, and Process Integration





Looking Forward

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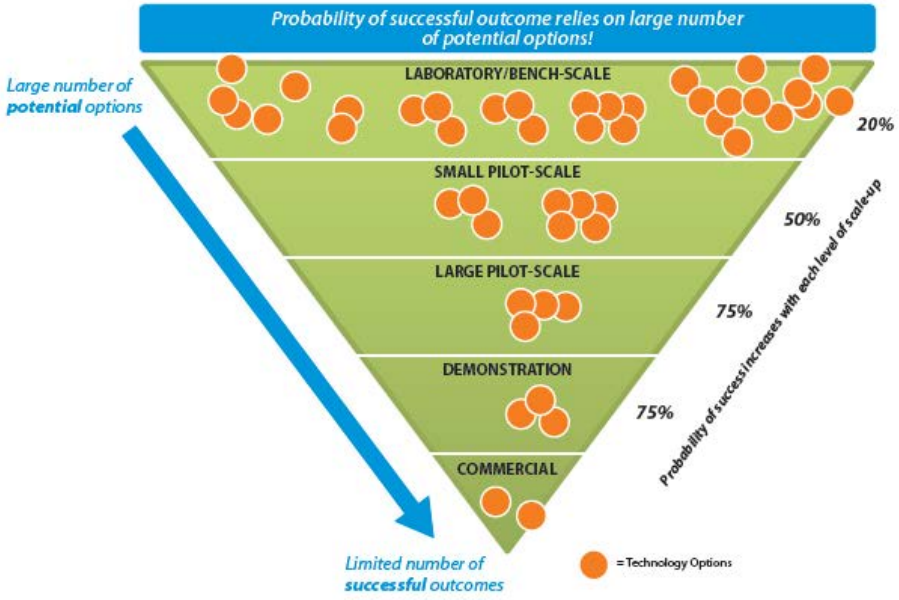
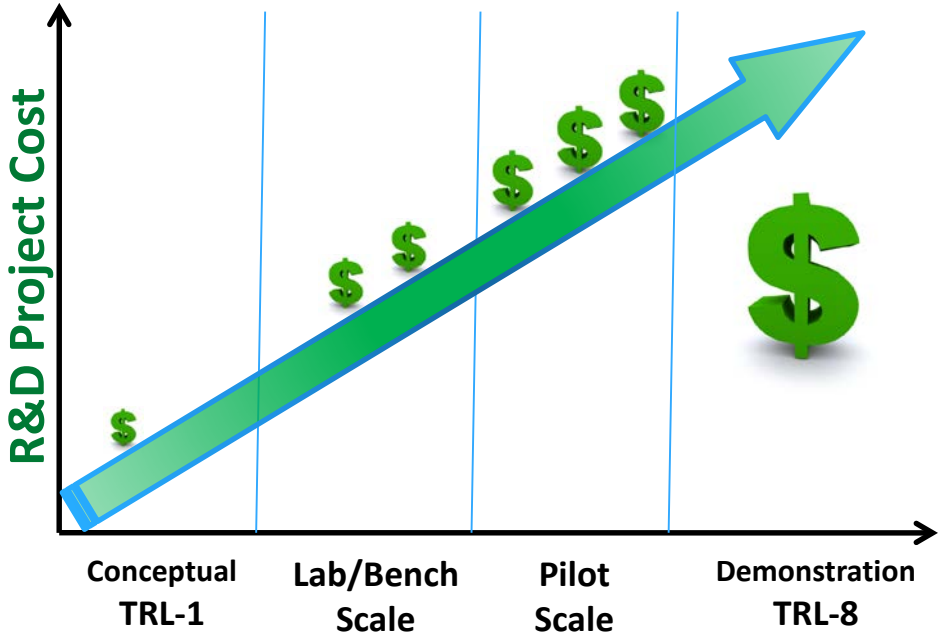
- **Transformational:** Development at Laboratory/Bench Scale

Laboratory / Bench-Scale

University of Southern California - A High Efficiency, Ultra-Compact Process for Pre-Combustion CO2 Capture



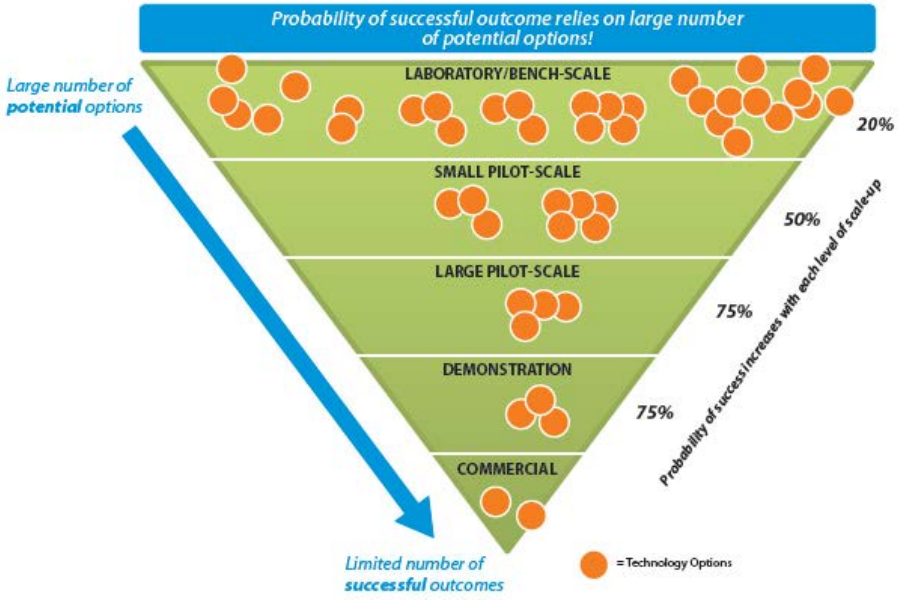


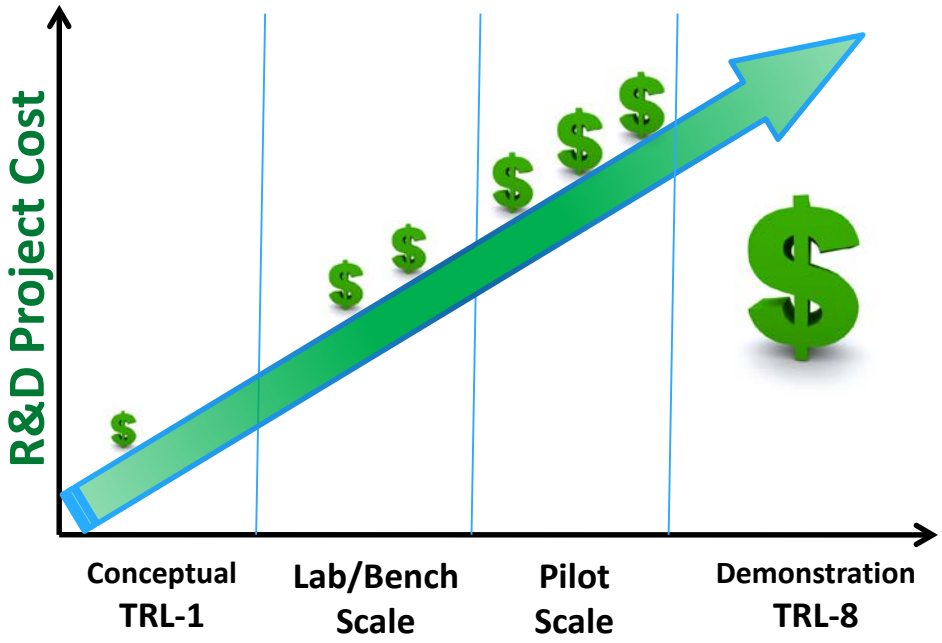
Looking Forward

- **2nd Generation:** Increased Focus on Pilot-Scale
- **Transformational:** Development at Laboratory/Bench Scale

Laboratory / Bench-Scale

Southern Research Institute
Combined Sorbent/WGS with Integrated Heat Management





Looking Forward

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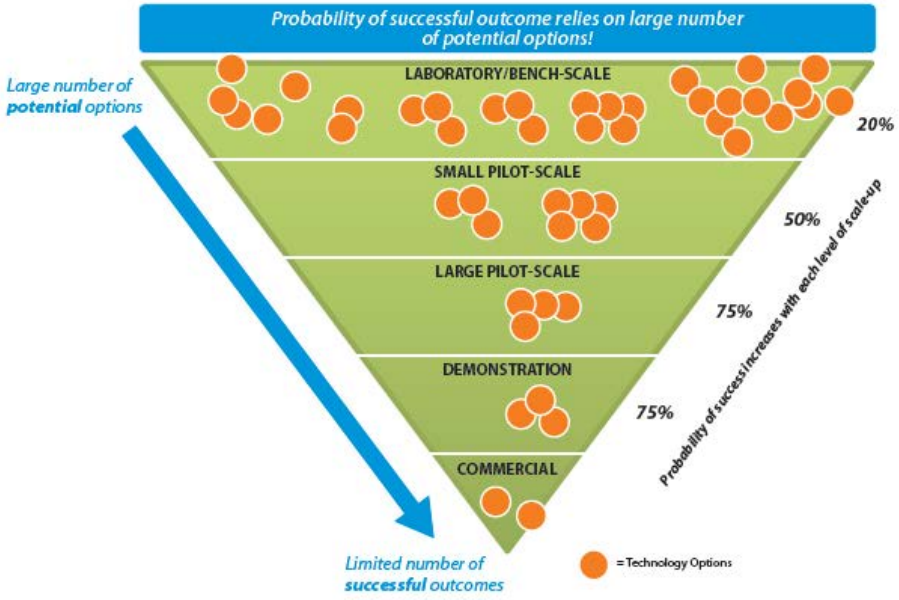
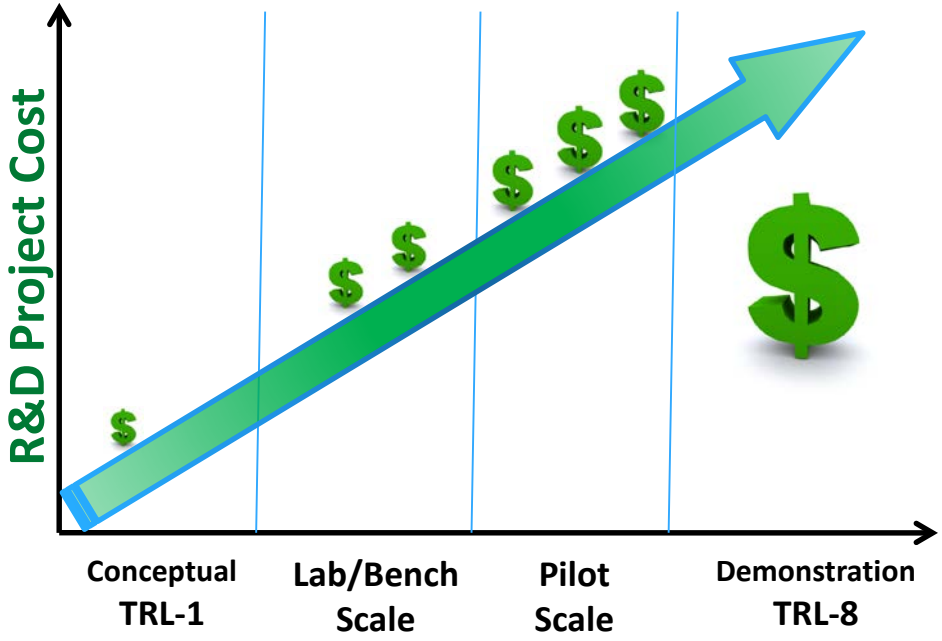
Laboratory / Bench-Scale

The Research Foundation of State University of New York
Sorption Enhanced Mixed Matrix Membranes



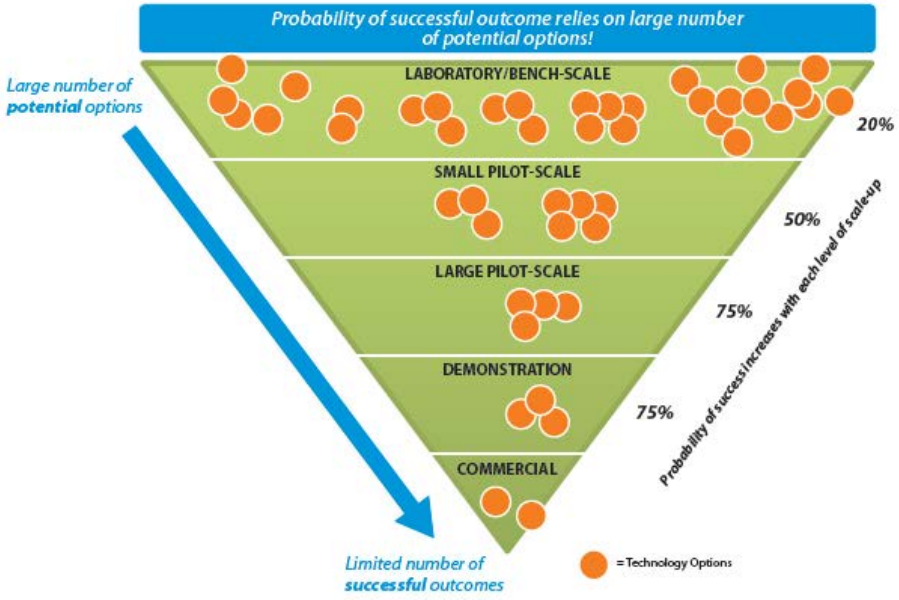


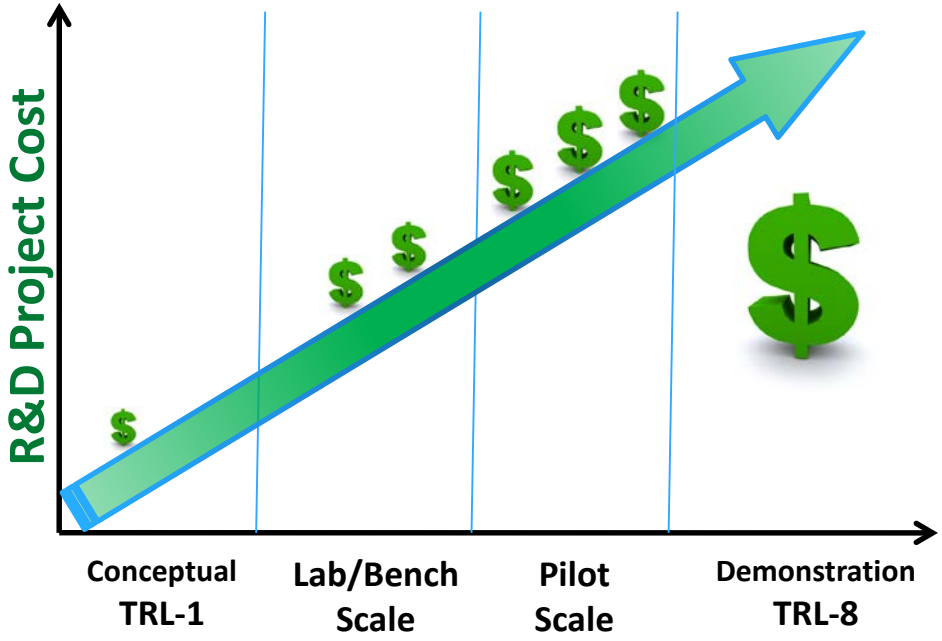
Looking Forward

- **2nd Generation:** Increased Focus on Pilot-Scale
- **Transformational:** Development at Laboratory/Bench Scale

Small Pilot-Scale

Linde, LLC
Slipstream Novel Amine-Based Post-Combustion Process





Looking Forward

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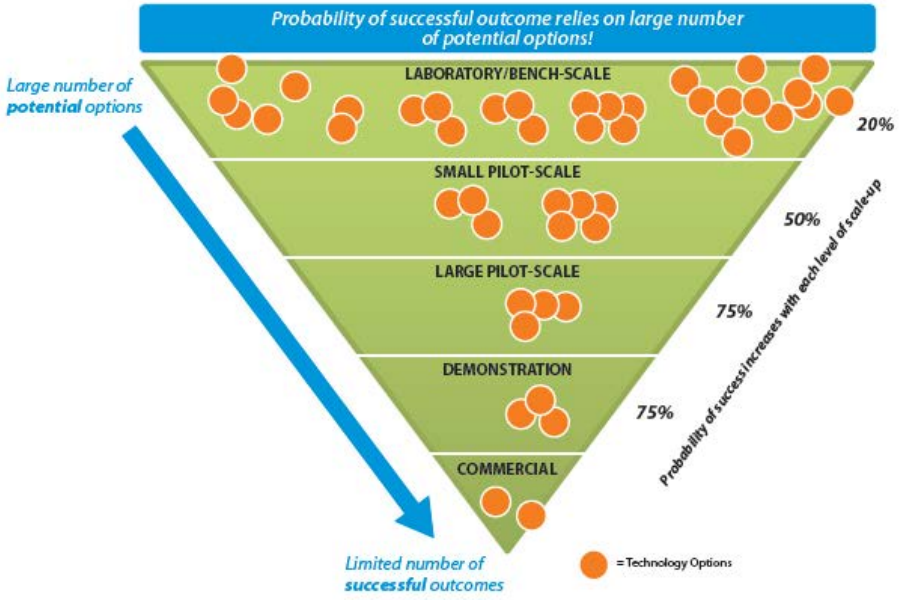
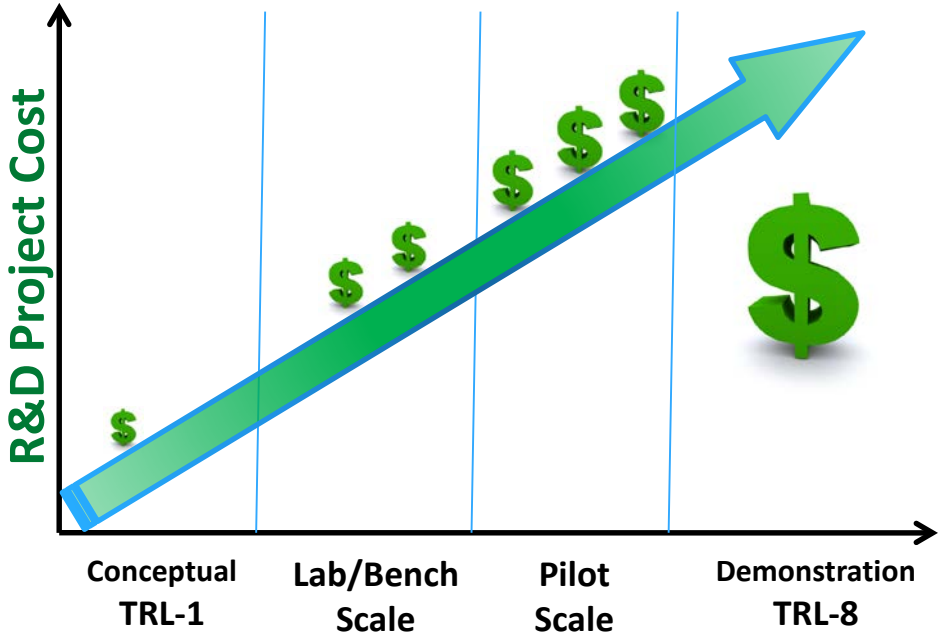
- **Transformational:** Development at Laboratory/Bench Scale

Small Pilot-Scale

University of Kentucky - Heat Integrated Post-combustion CO_2 Capture System Using the MHPSA Advanced Solvent





Looking Forward

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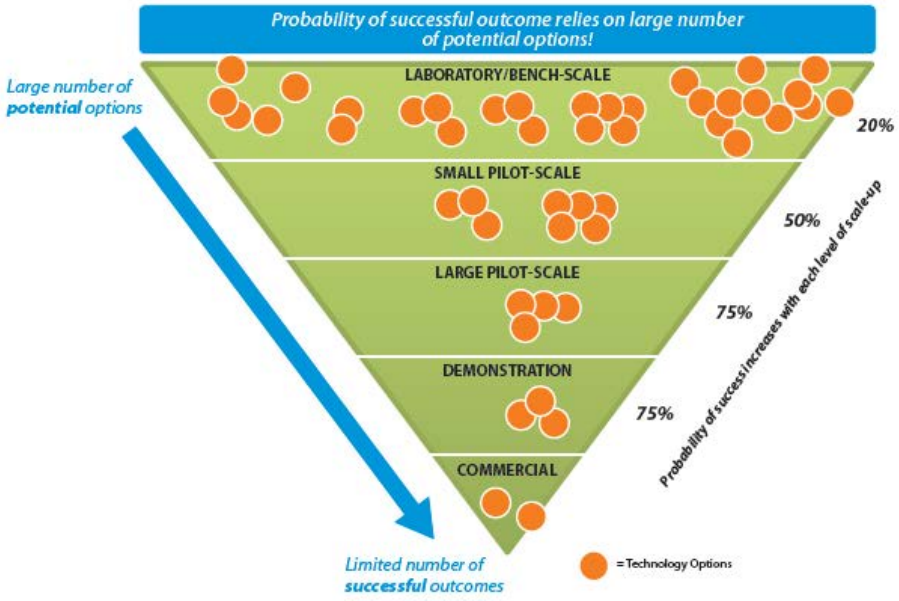
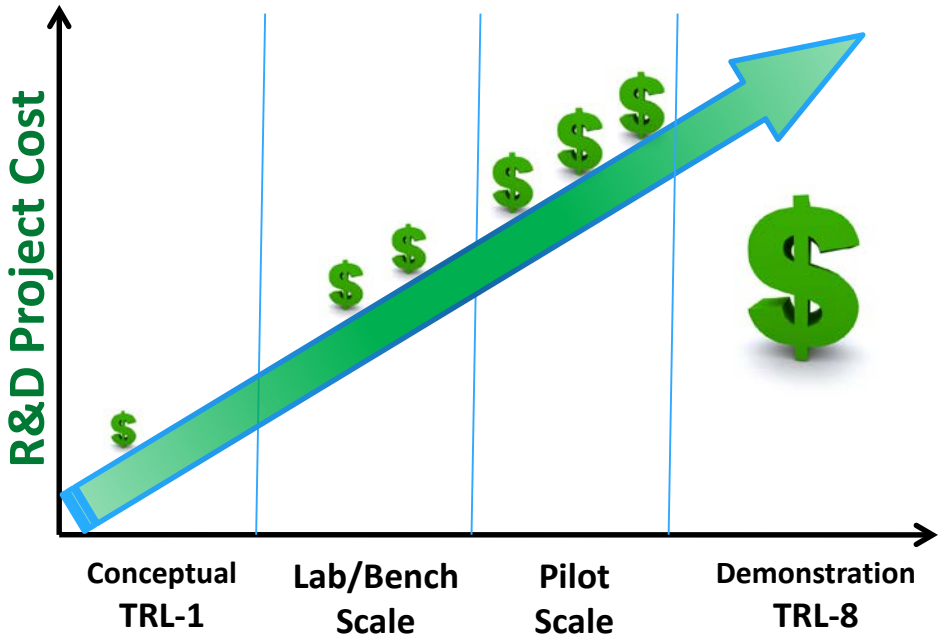
- **Transformational:** Development at Laboratory/Bench Scale

Small Pilot-Scale

General Electric
Novel Aminosilicone Solvent





Looking Forward

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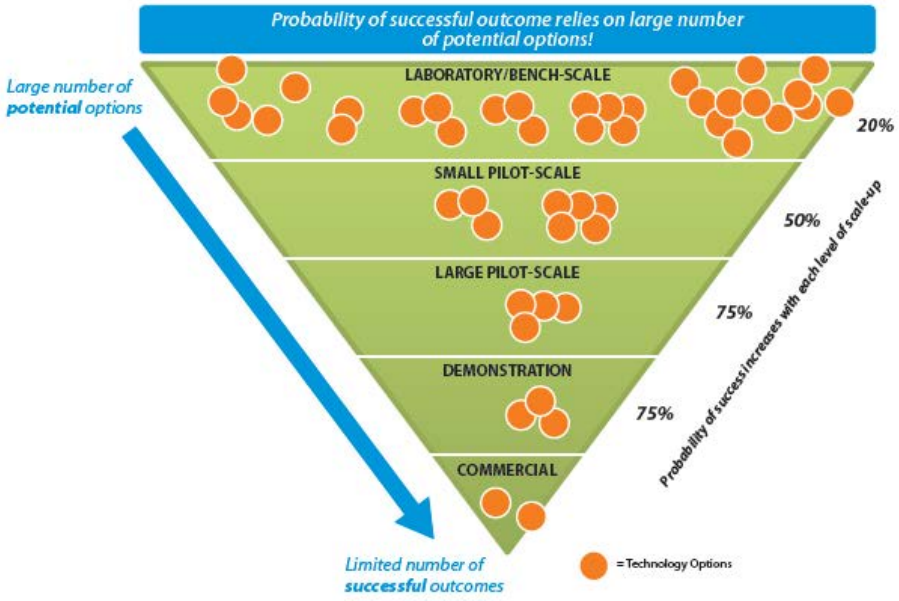
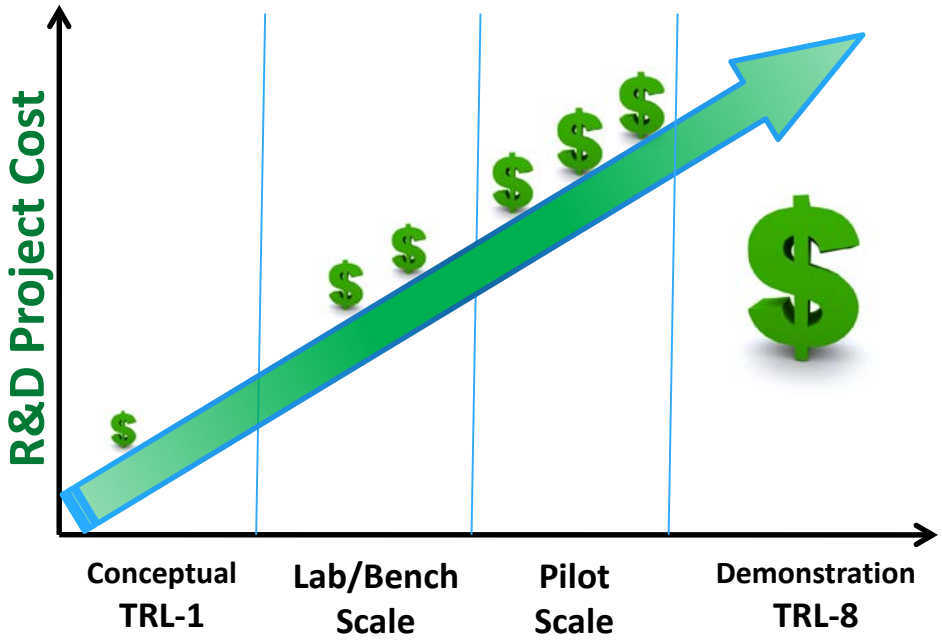
- **Transformational:** Development at Laboratory/Bench Scale

Small Pilot-Scale

ION Engineering
Amine Solvent in Ionic Liquid





Looking Forward

- **2nd Generation:** Increased Focus on Pilot-Scale
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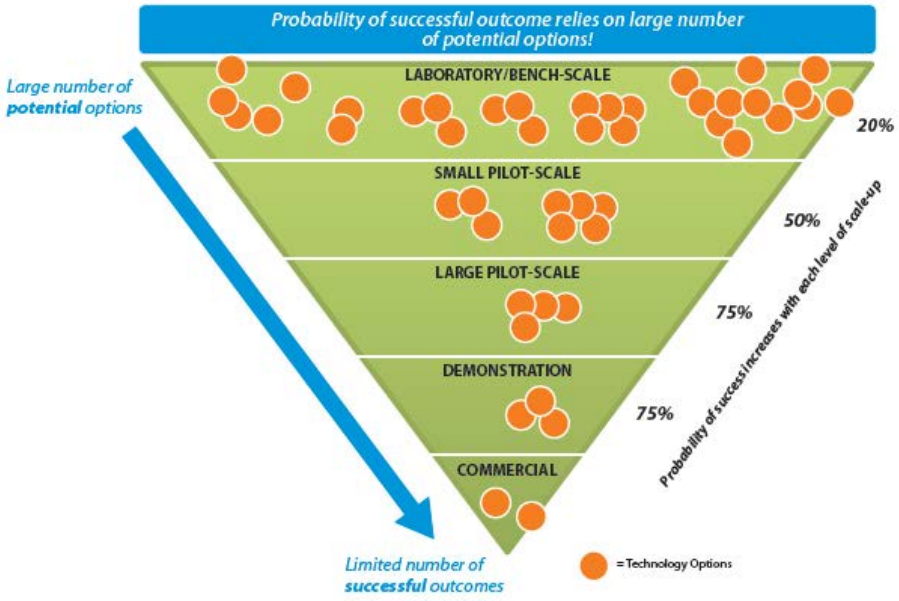
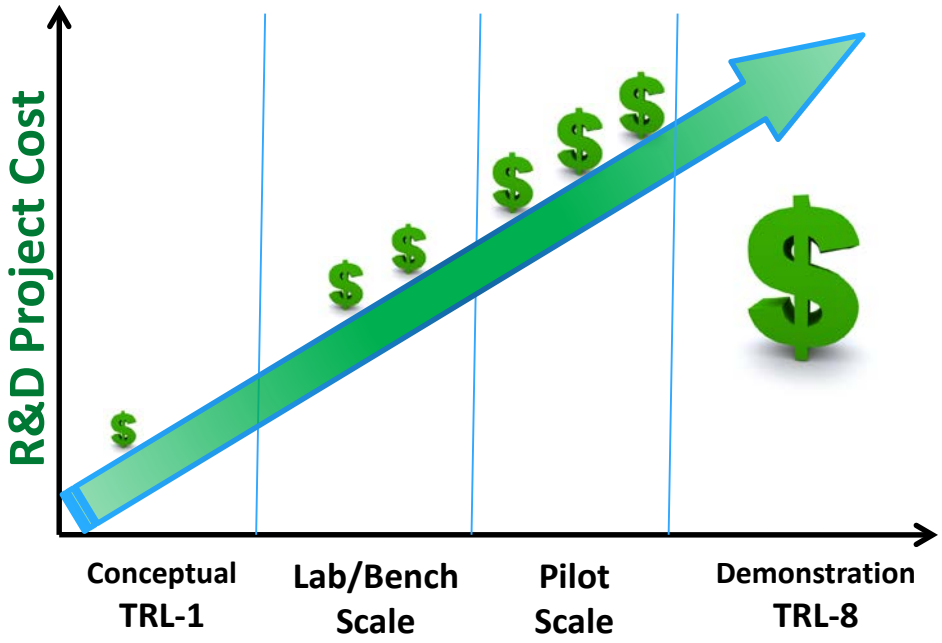
Small Pilot-Scale

TDA Research, Inc.
Alkalized Alumina Solid Sorbent





Looking Forward

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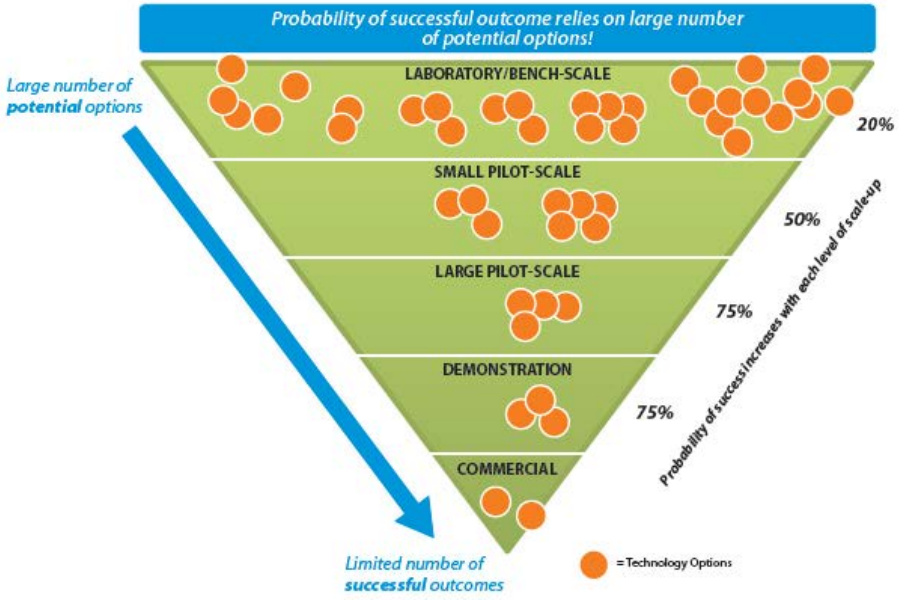
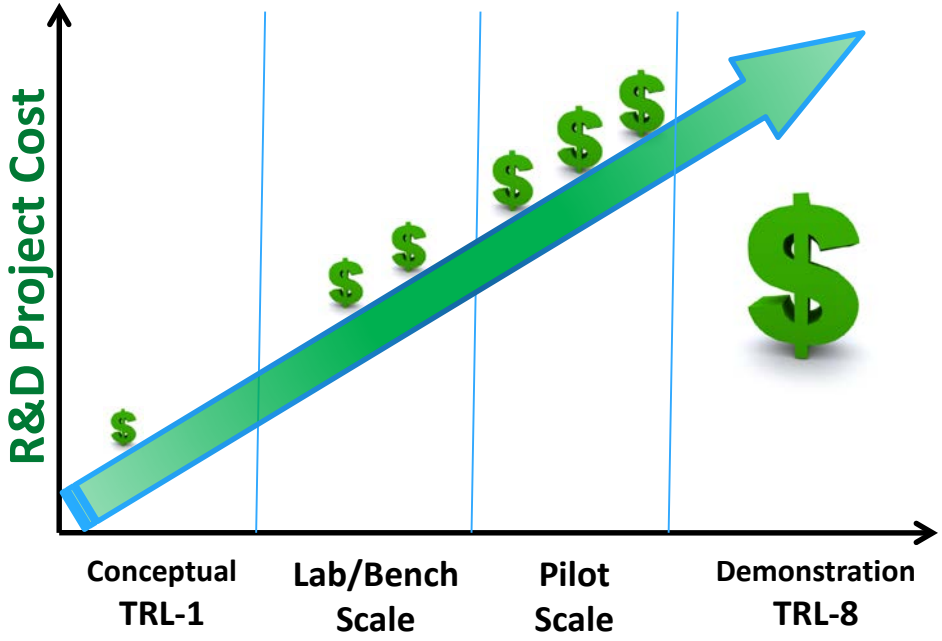
Small Pilot-Scale

Membrane Technology & Research
Polymeric Membranes





Looking Forward

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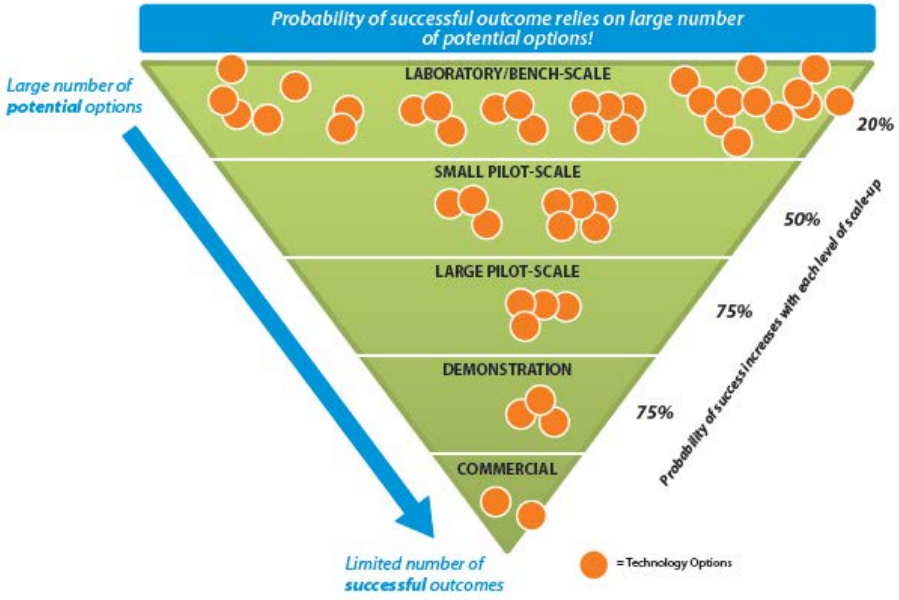
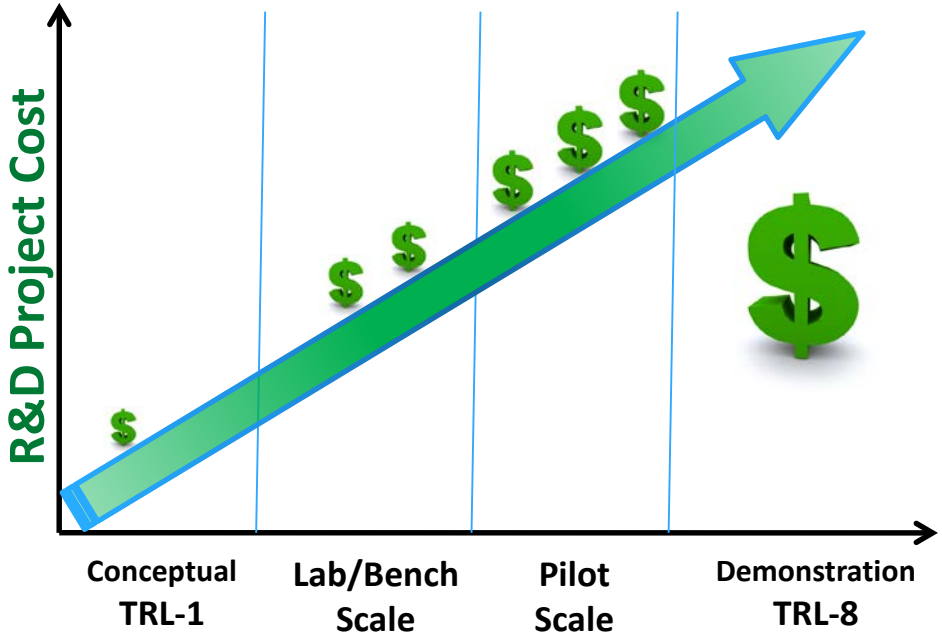
Small Pilot-Scale

Gas Technology Institute
Hollow-Fiber-Membrane Contactor with aMDEA Solvent





Looking Forward

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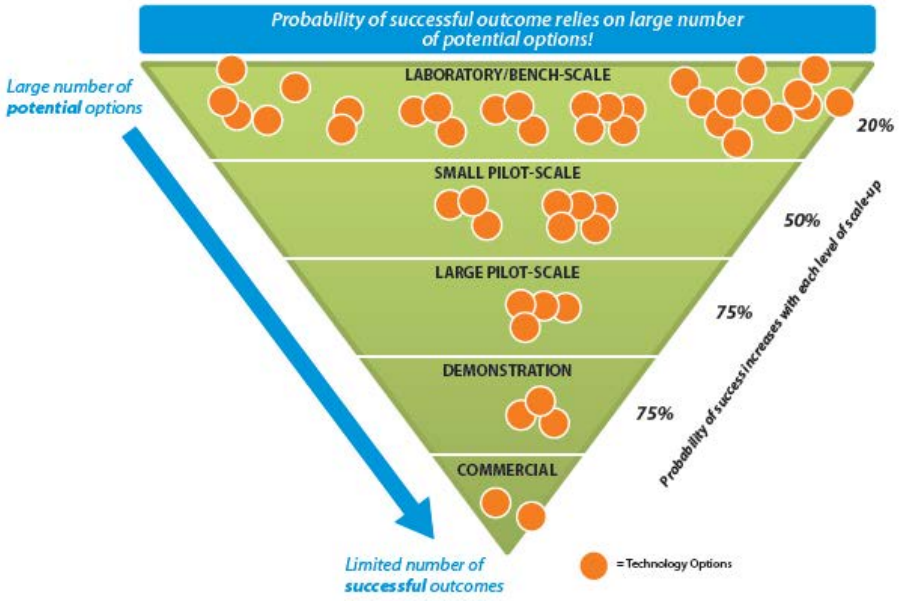
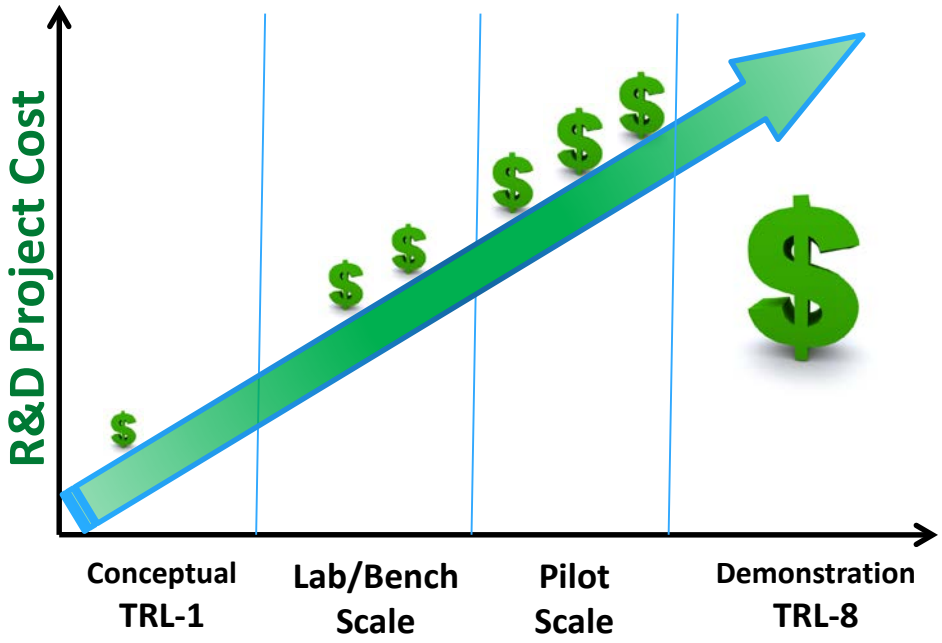
Small Pilot-Scale

FuelCell Energy Inc.
Combined Electric Power and CO_2 Separation (CEPACS) System



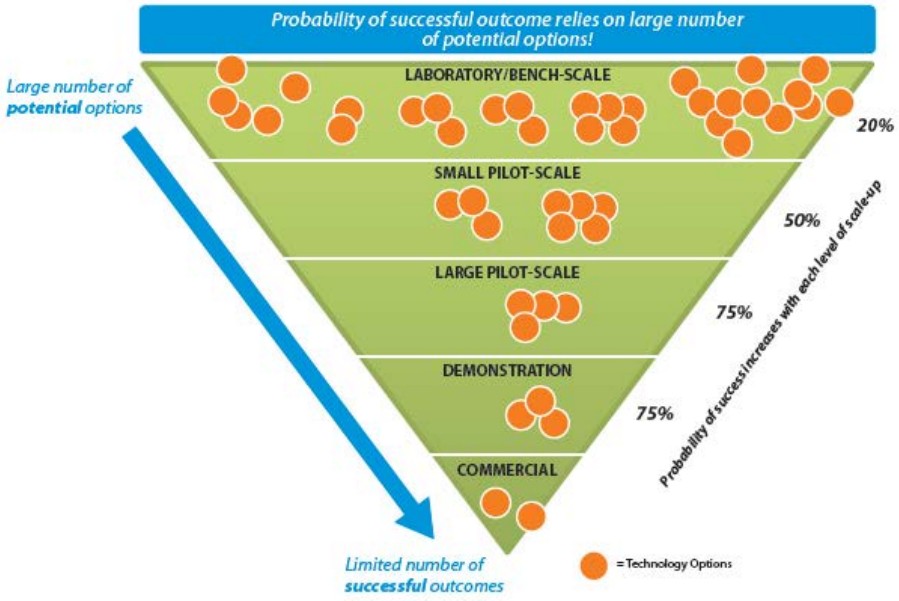


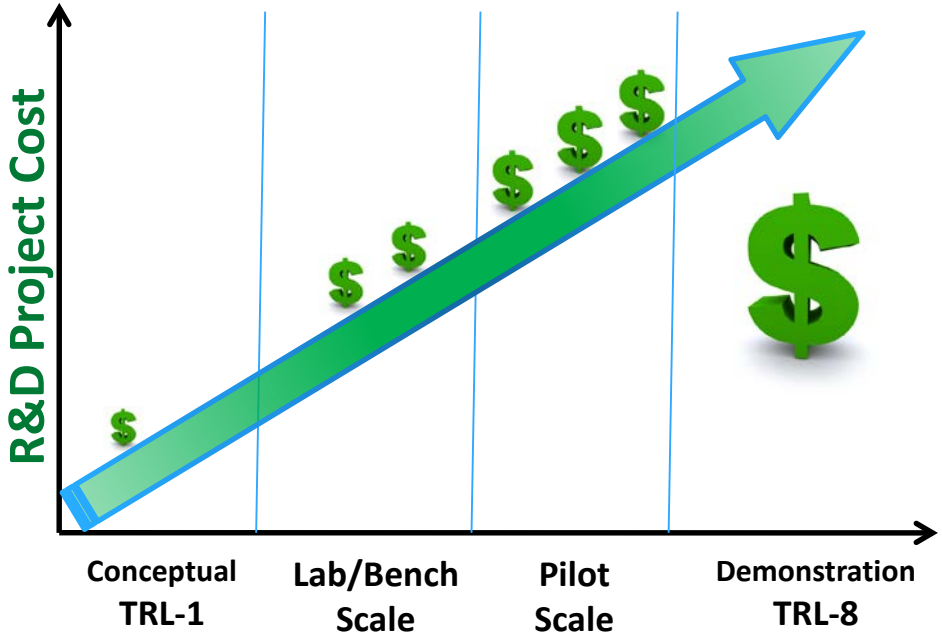
Looking Forward

- **2nd Generation:** Increased Focus on Pilot-Scale
- **Transformational:** Development at Laboratory/Bench Scale

Small Pilot-Scale

SRI International
CO2 Capture Using AC-ABC Process





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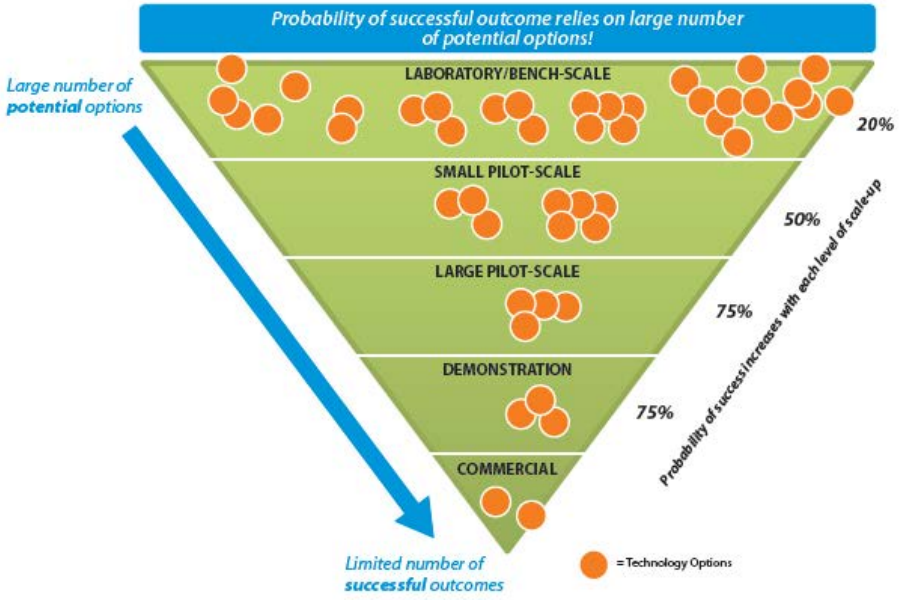
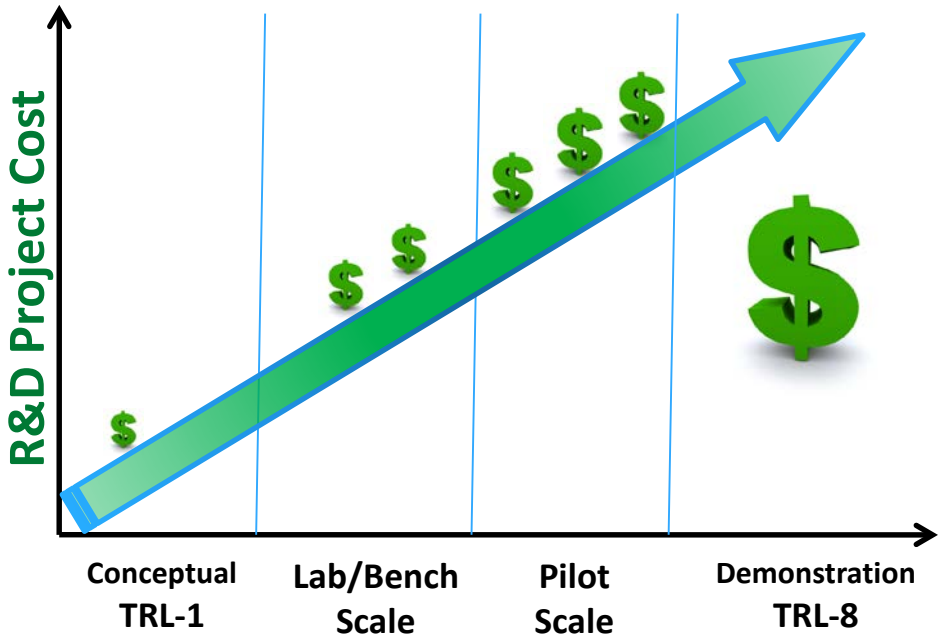
Small Pilot-Scale

TDA, Inc.
High Capacity Regenerable Sorbent



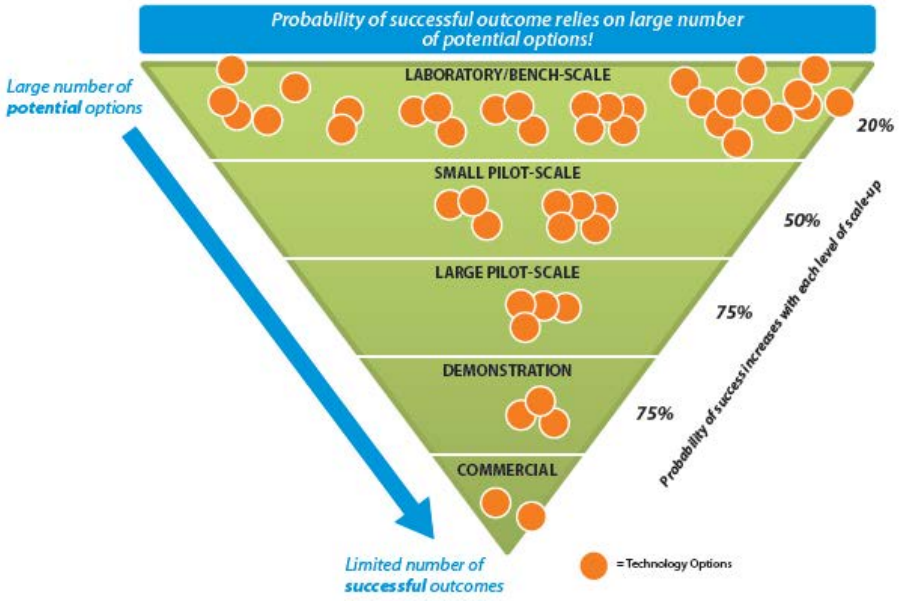


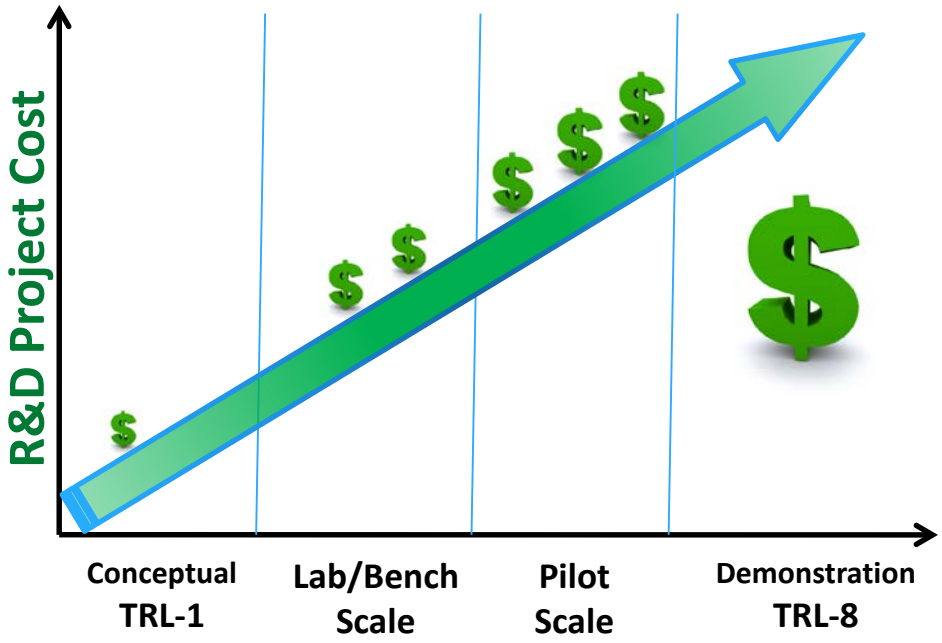
Looking Forward

- **2nd Generation:** Increased Focus on Pilot-Scale
- **Transformational:** Development at Laboratory/Bench Scale

Large Pilot-Scale

Southern Company Services
Waste Heat Integration





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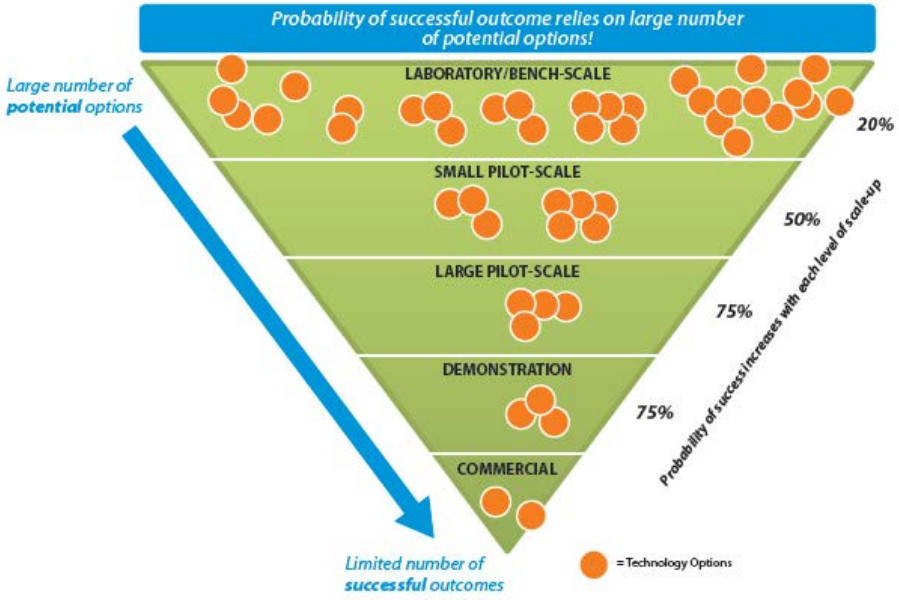
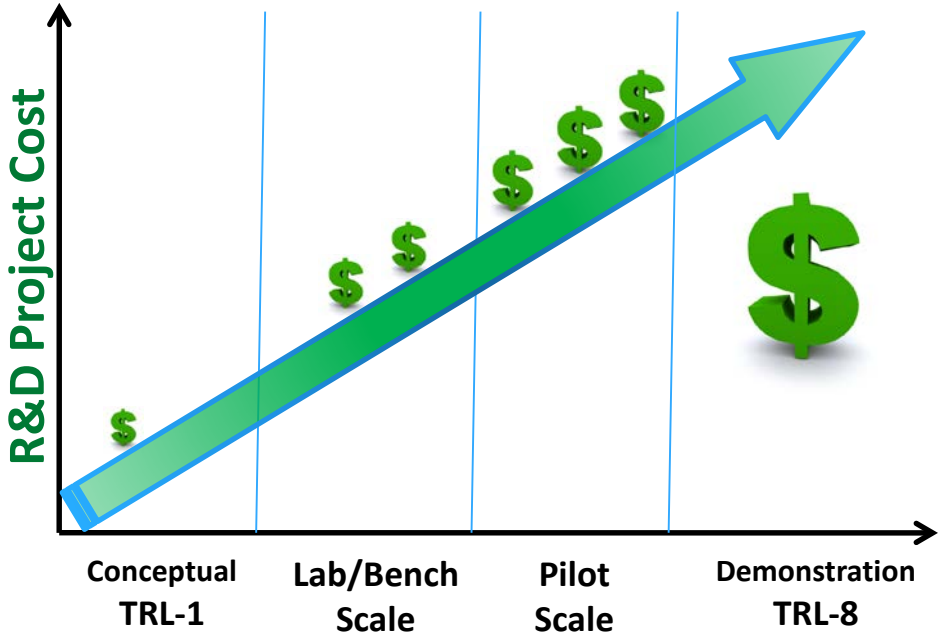
Large Pilot-Scale

University of Illinois
Linde/BASF CO_2 Capture Technology





Looking Forward

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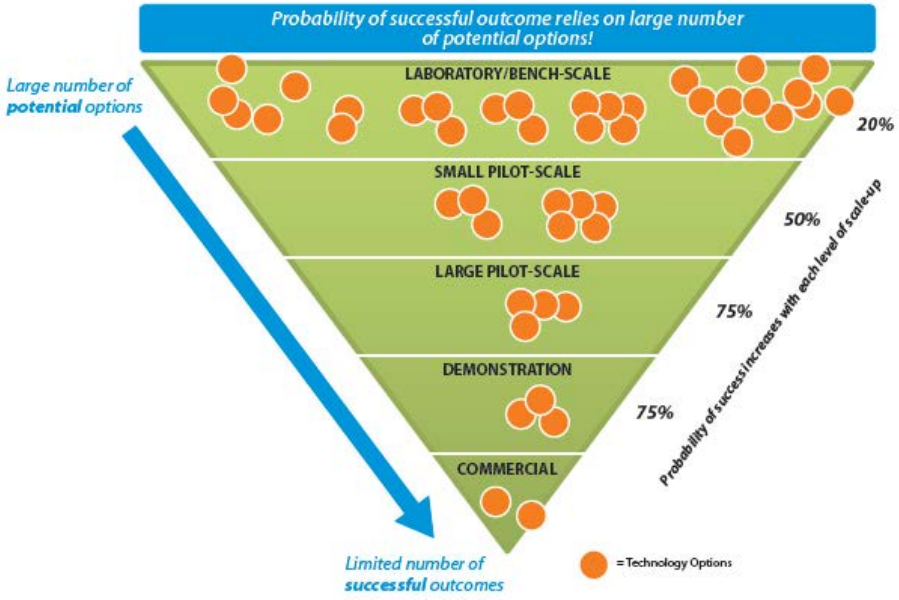
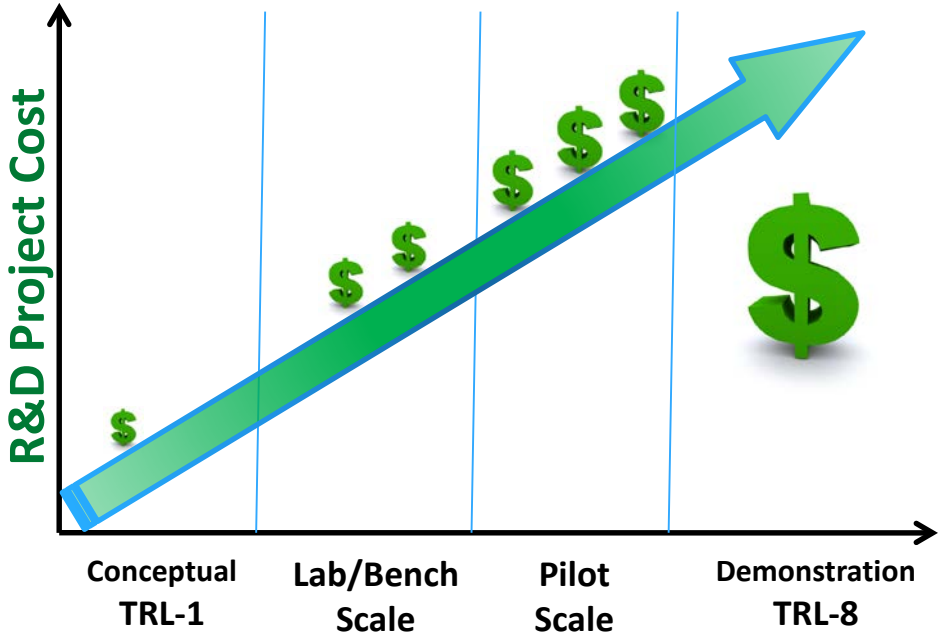
- **Transformational:** Development at Laboratory/Bench Scale

Large Pilot-Scale

Alstom Power
Improvements to Chilled Ammonia Process





Looking Forward

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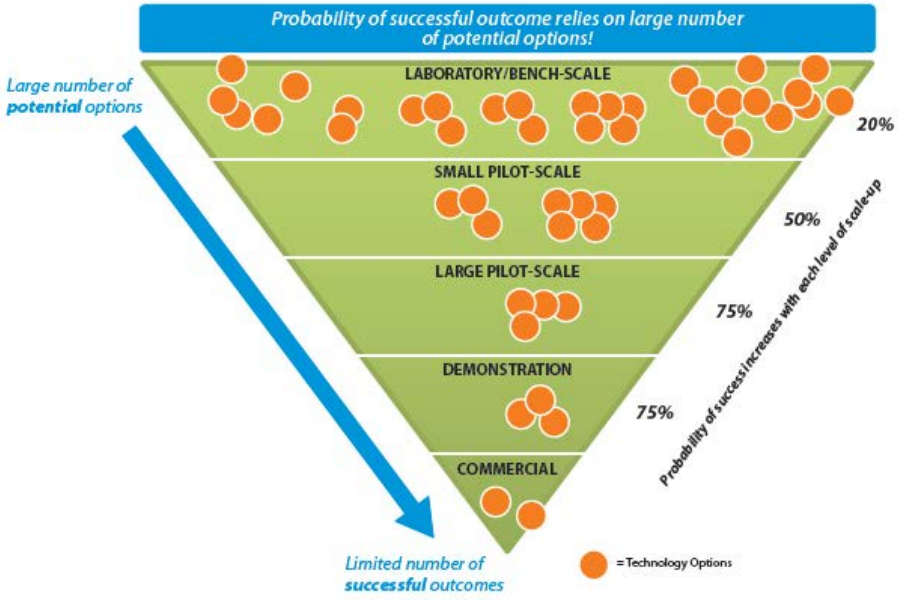
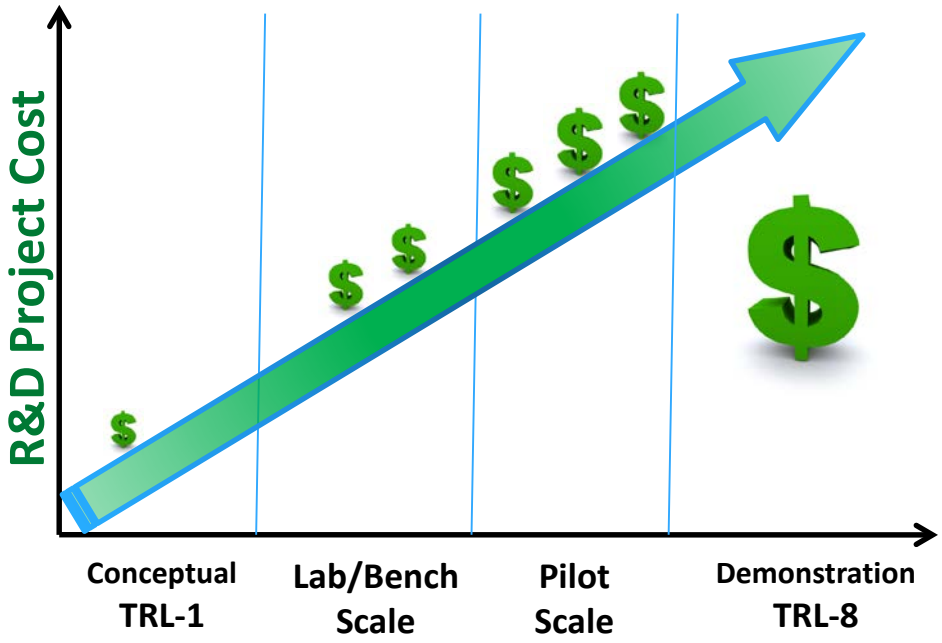
- **Transformational:** Development at Laboratory/Bench Scale

Large Pilot-Scale

Southern Company Services
Process Improvements/Advanced Solvent





Looking Forward

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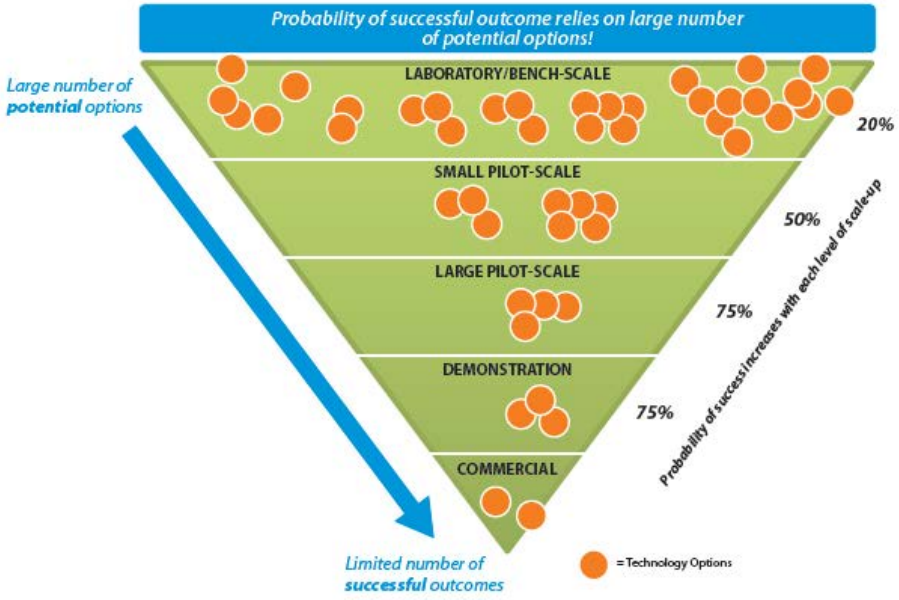
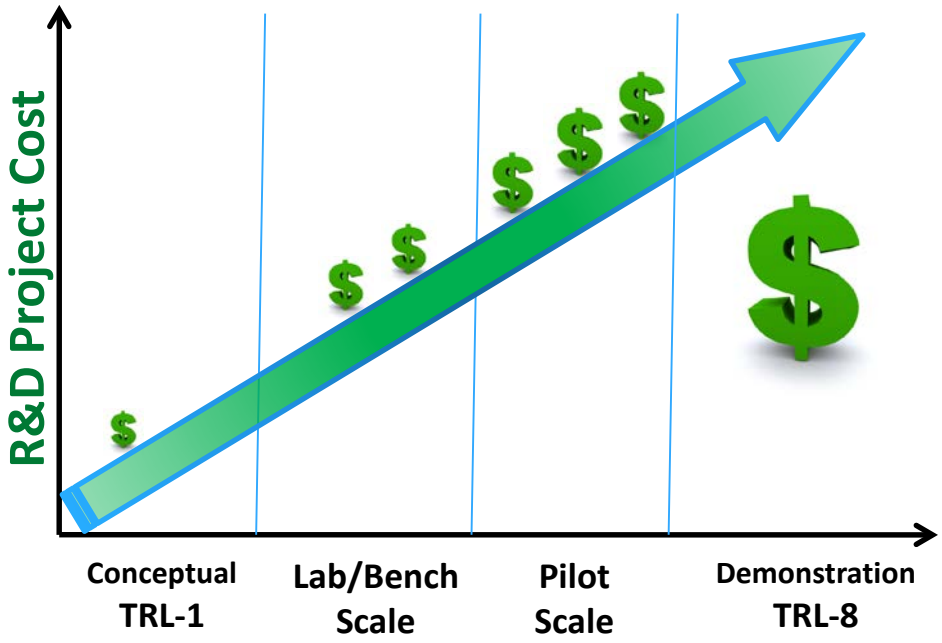
Large Pilot-Scale

University of Kentucky
Heat Integrated Capture System





Looking Forward

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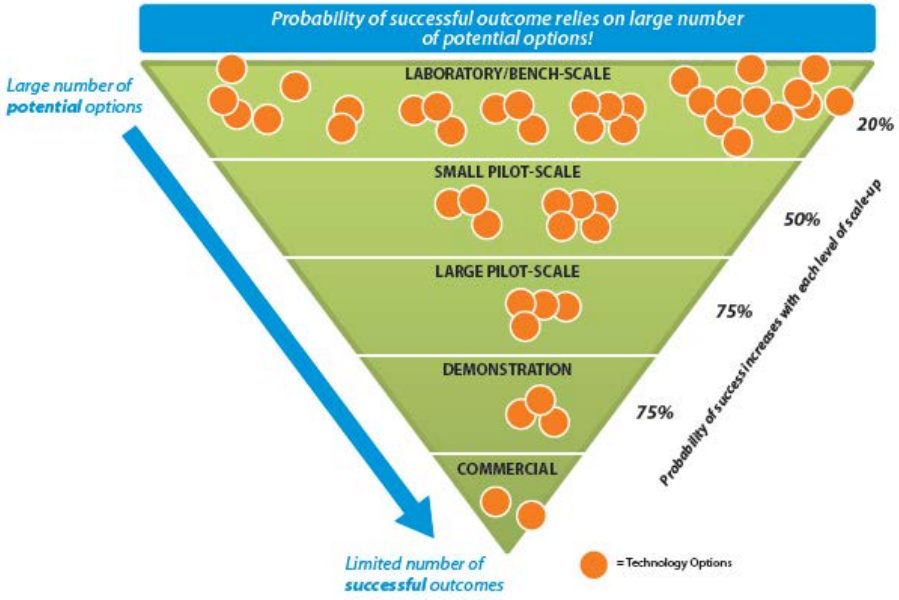
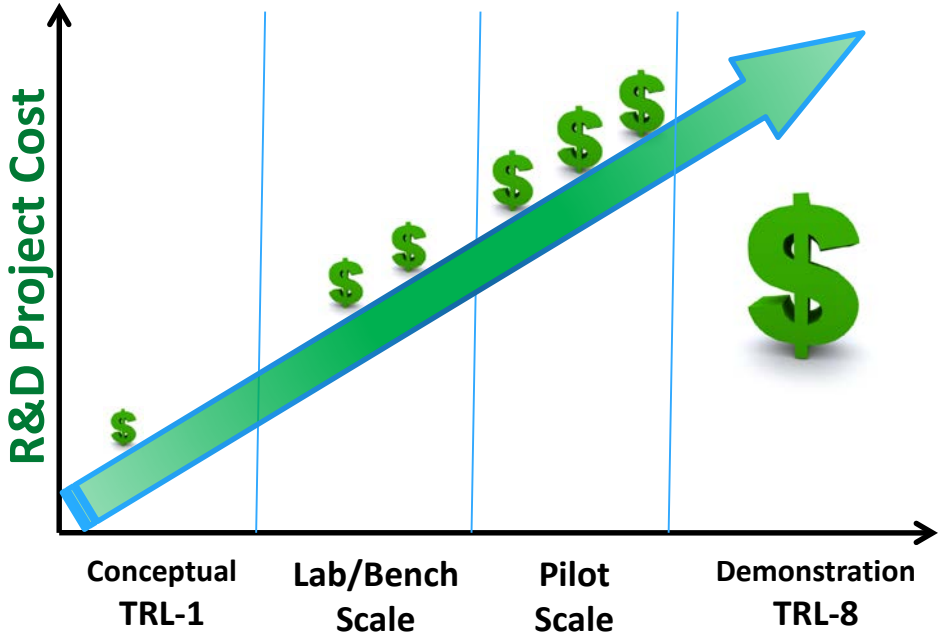
- **Transformational:** Development at Laboratory/Bench Scale

Large Pilot-Scale

General Electric
Novel Aminosilicone Solvent





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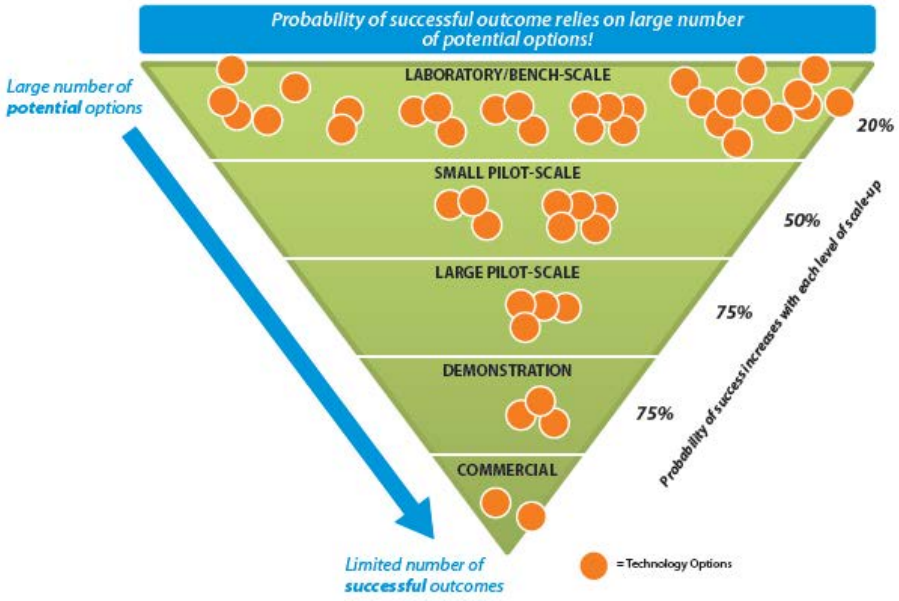
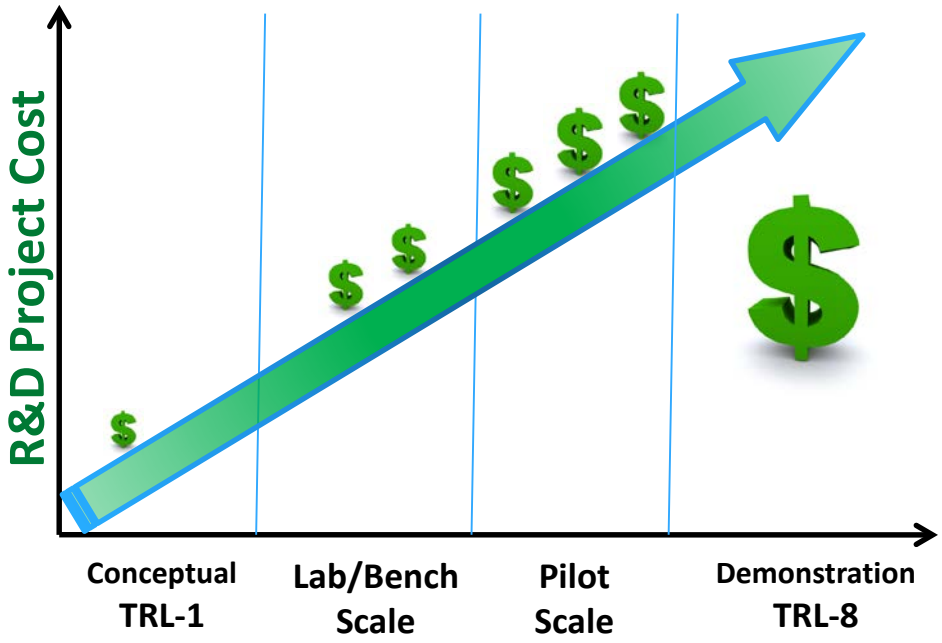
Large Pilot-Scale

NRG CO_2NCEPT
VeloxoTherm™ Solid Sorbent Capture System





Looking Forward

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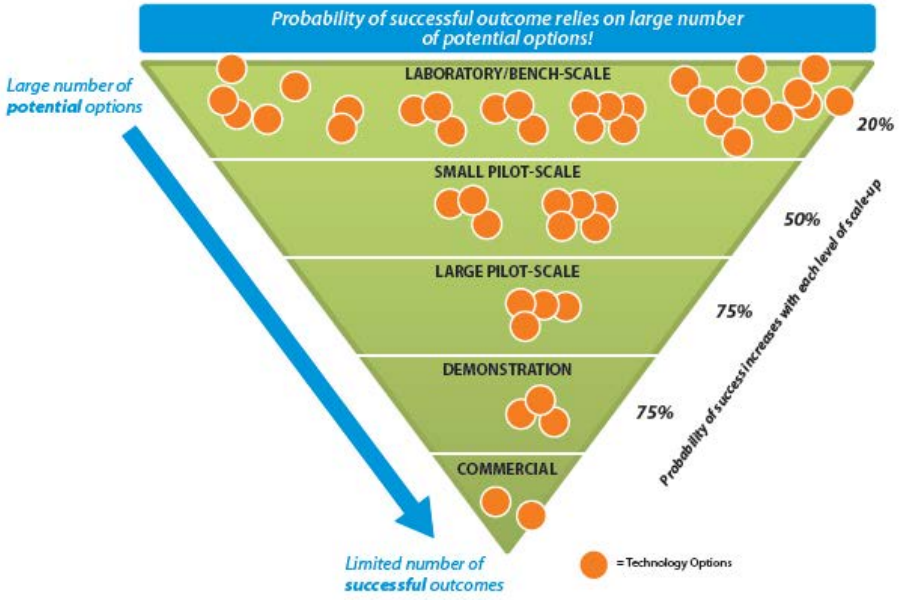
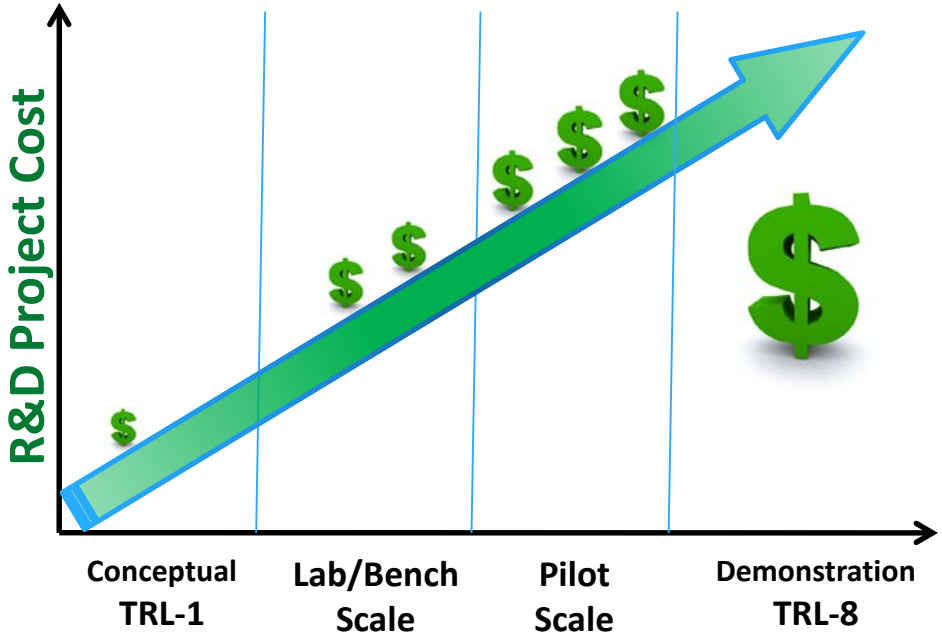
Large Pilot-Scale

Dresser-Rand
Supersonic CO_2 Compressor





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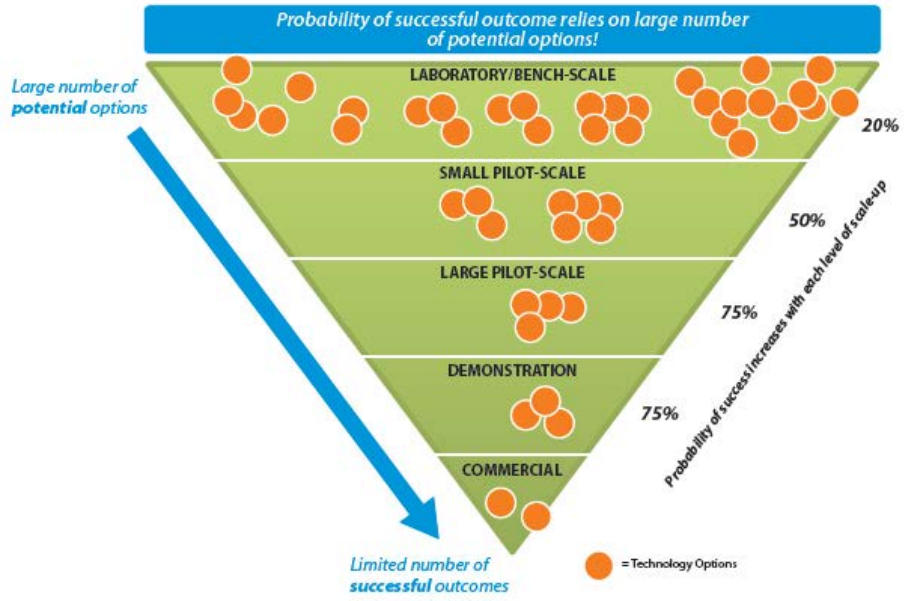
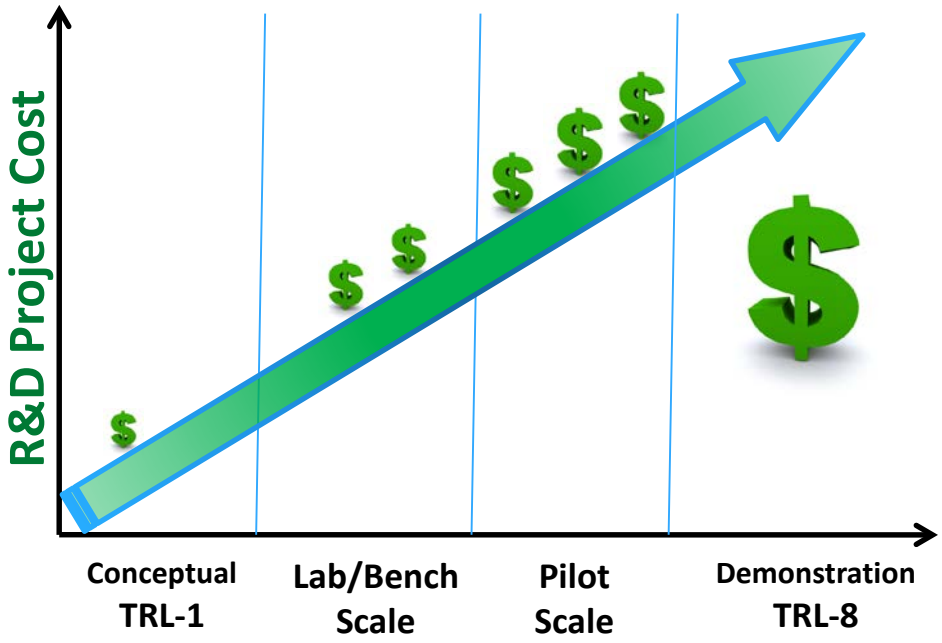
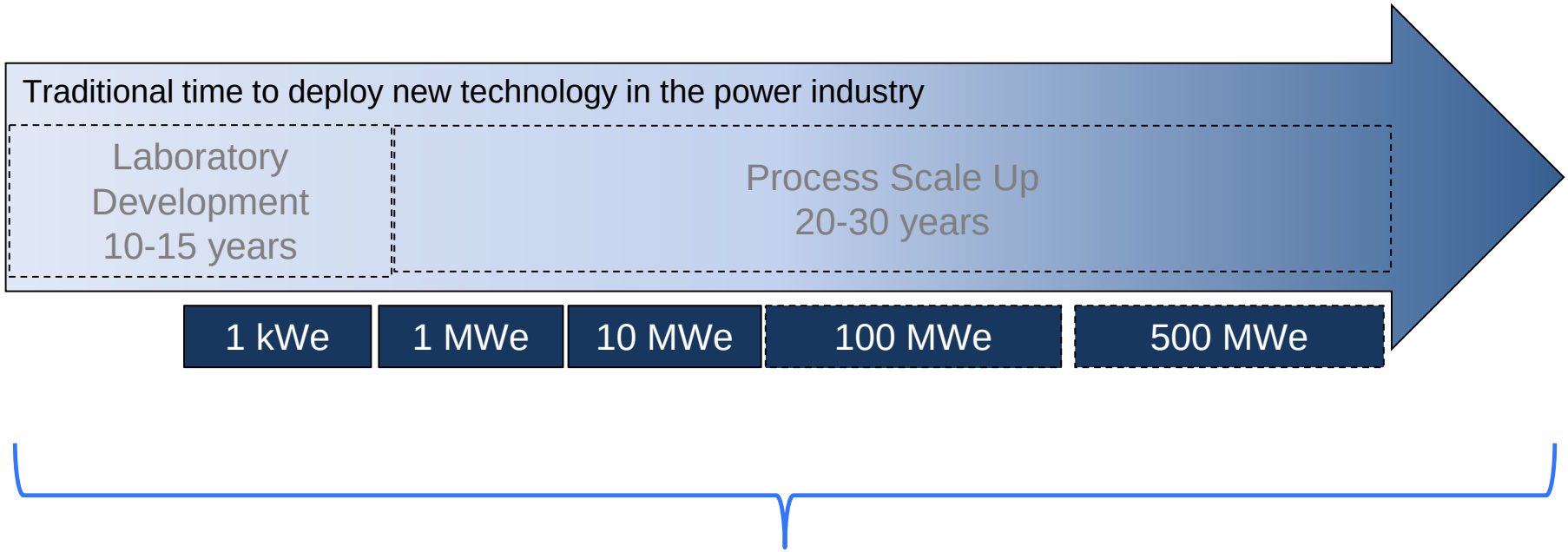




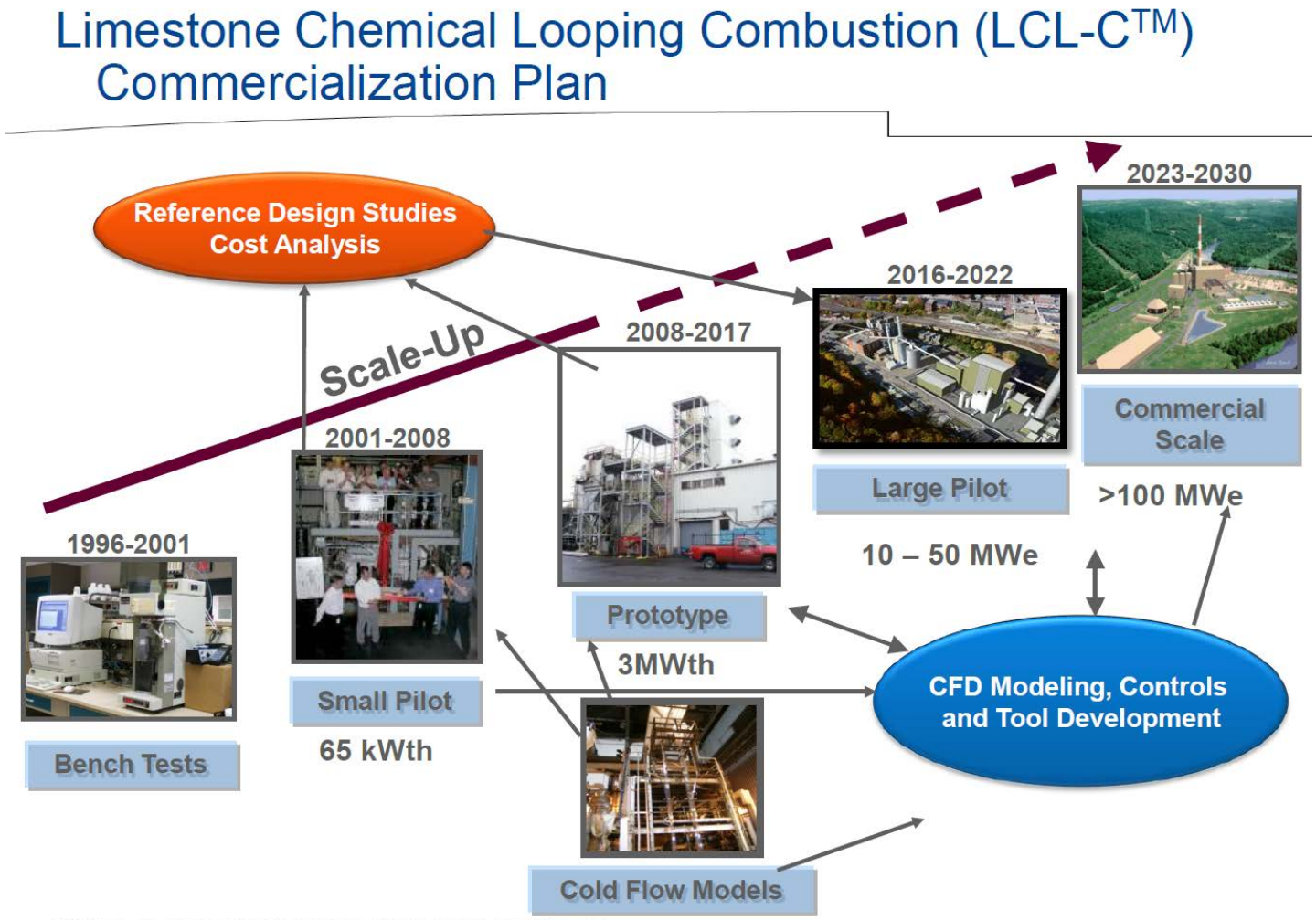
Challenge:
Accelerate Development/Scale Up



30 to 45 Years
R&D to Deployment

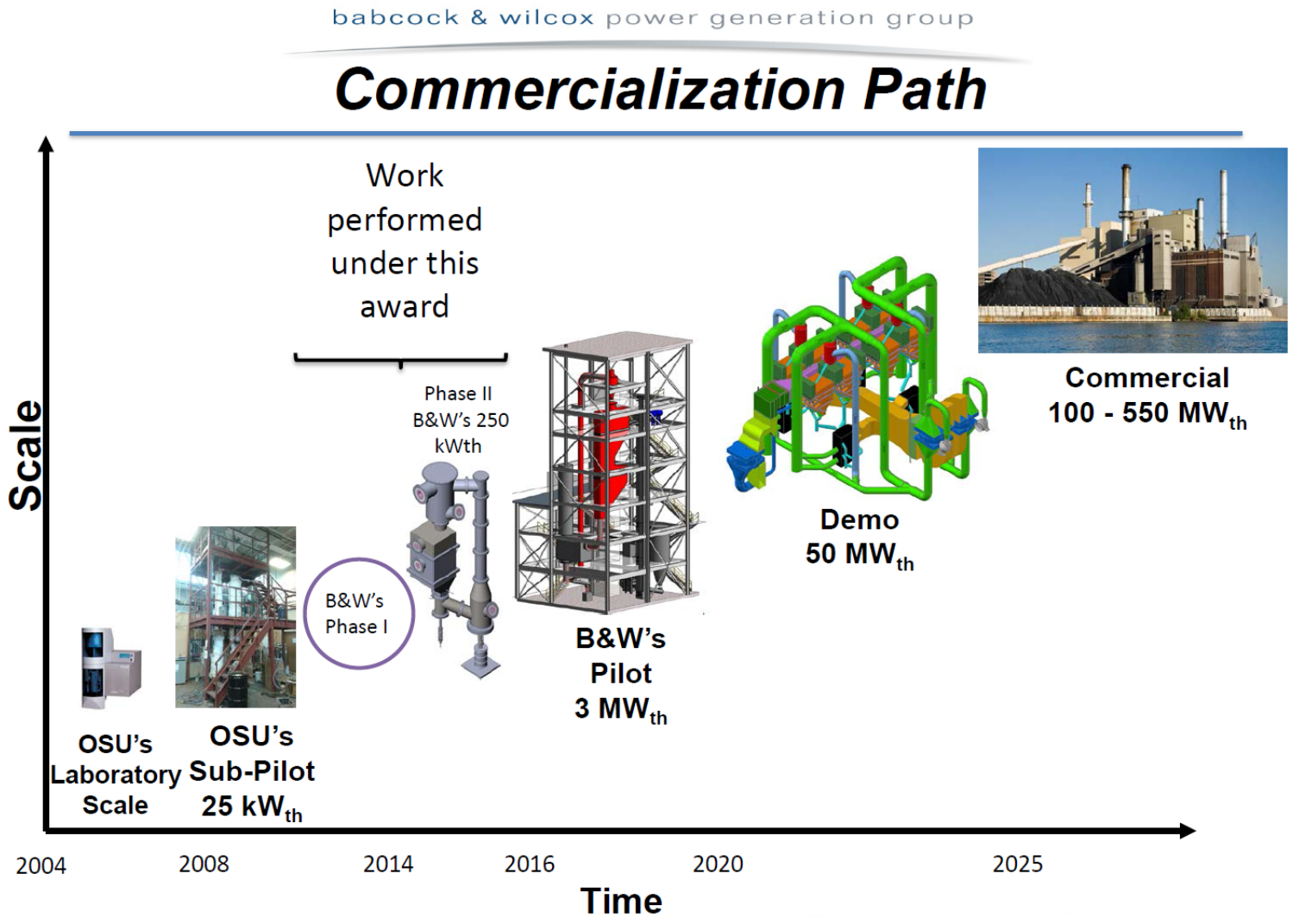
2010 2015 2020 2025 2030 2035 2040 2045 2050

Alstom
LCL-C™ Commercialization Plan



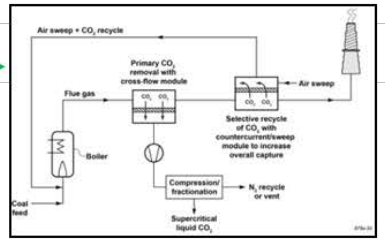
ALSTOM

Ohio State University/Babcock & Wilcox
CLC Commercialization Pathway



Membrane Technology and Research, Inc.
CO_2 Capture Development Timeline

Feasibility study (DE-NT43085)
- Sweep concept proposed
- Polaris membrane conceived

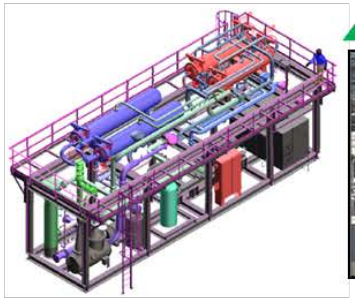


APS Red Hawk NGCC Demo
- First Polaris flue gas test
- 250 lb/d CO_2 used for algae farm

APS Cholla Demo (DE-NT5312)
- First Polaris coal flue gas test
- 1 TPD CO_2 captured (50 kW_e)

NCCC 1 MW_e Demo (DE-FE5795)
- 10,000 hours of 1 TPD system operation
- 1 MW_e (20 TPD) system operation

Low Pressure Mega Module (DE-NT7553)
- Design and build a 500 m^2 optimized module



Hybrid Capture (DE-FE13118)
- Membrane-solvent hybrids with UT, Austin

B&W Integrated (DE-FE26414)

Future 10 MW_e Large Pilot

FuelCell Energy, Inc.

Electrochemical Membrane Technology Development Road Map

1921 — MCFC Basic Technology Development

Molten Carbonate Fuel Cell (MCFC) Invention

1992 — MCFC Power Plant Commercialization

MCFC Manufacturing Plant

2003

MCFC Power Plant Products

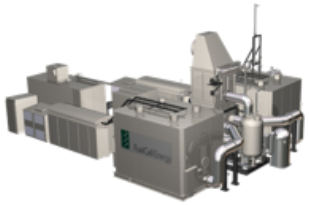
2010 — Combined Electric Power and Carbon-Dioxide Separation (CEPACS) Conceptualization

2016

Bench Scale Tests (100 tons/year)

2019 — Small Pilot Plant Design, Fabrication & Test

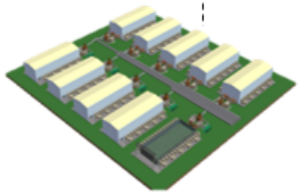
Small CEPACS Pilot Plant (40 Tons/day)

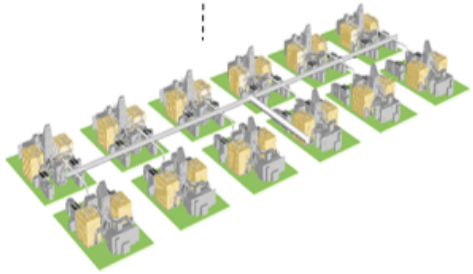


2024 — Large Pilot Plant Design, Fabrication & Test; CEPACS Systems for Coal Power Plants

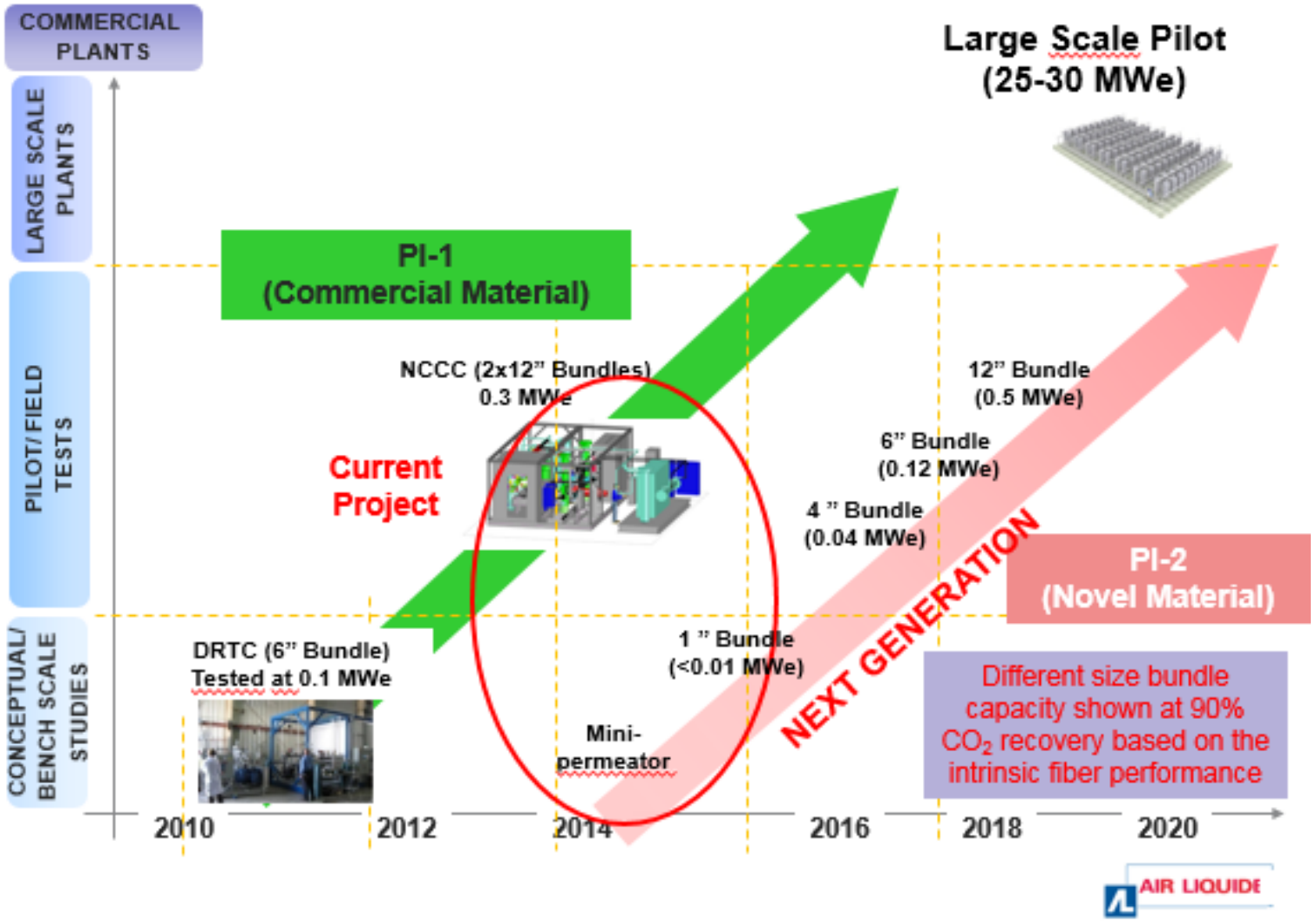
Large CEPACS Pilot Plant (500 Tons/day)

550 MW Coal Plant Carbon Capture

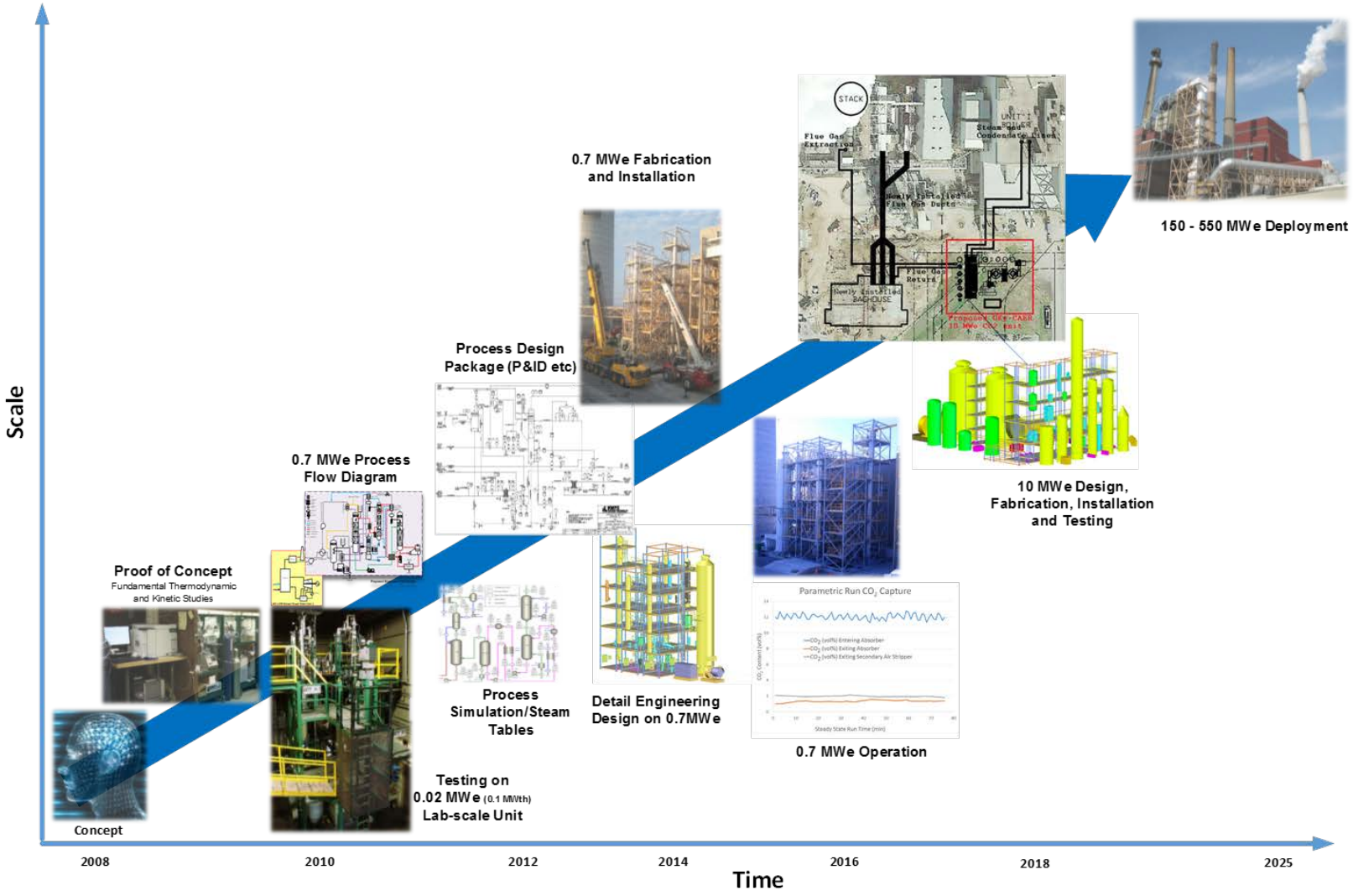




Air Liquide
Sub-Ambient CO_2 Capture Development Plan



University of Kentucky CAER
Heat Integrated Advanced Solvent System



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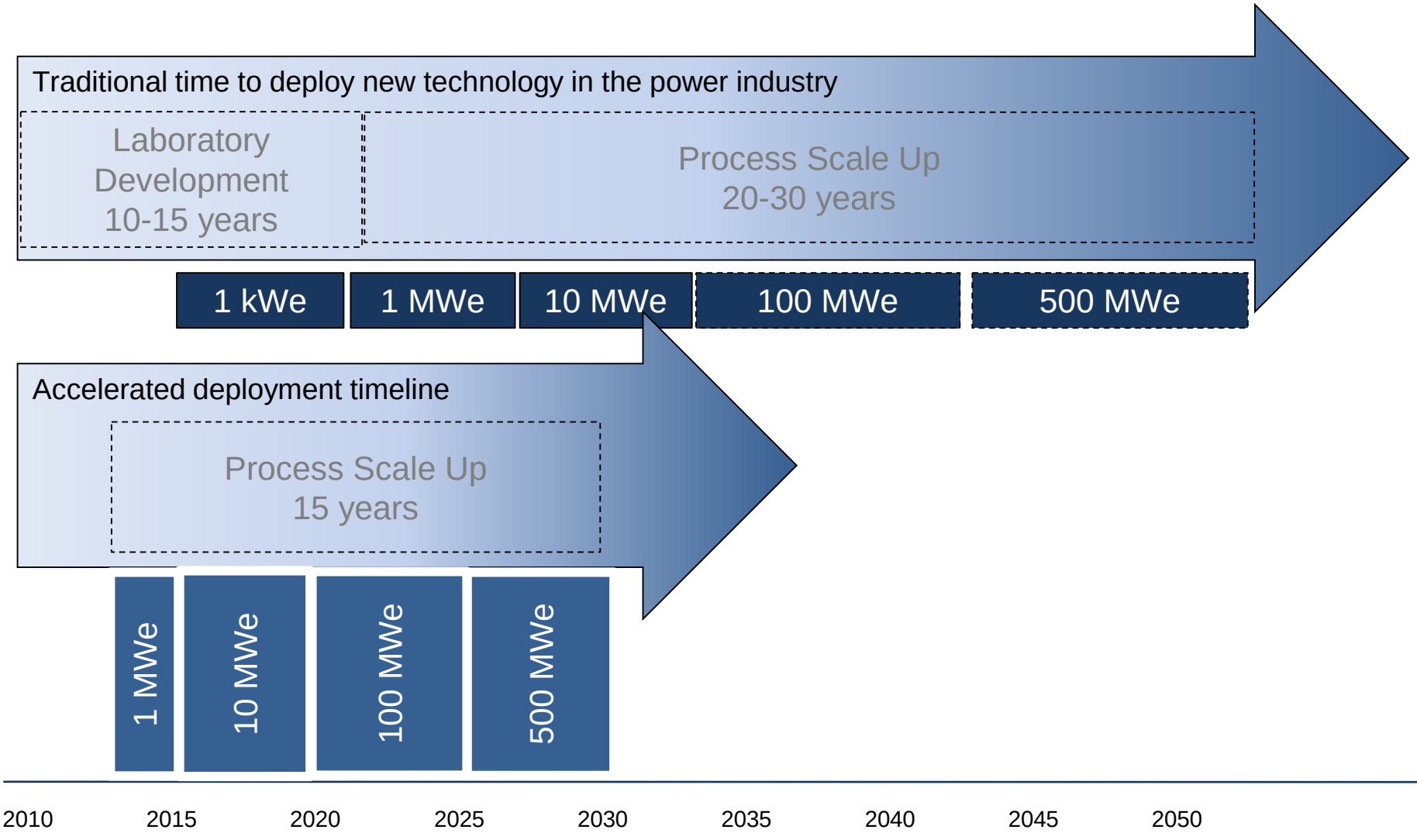
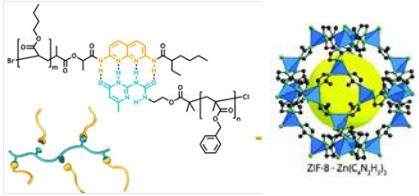
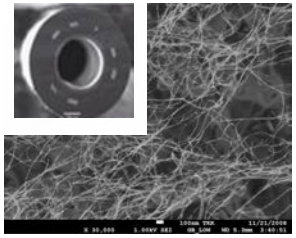


NETL's Research & Innovation Center Approach: Integrated Technology Development

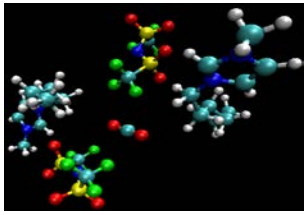
Material Synthesis

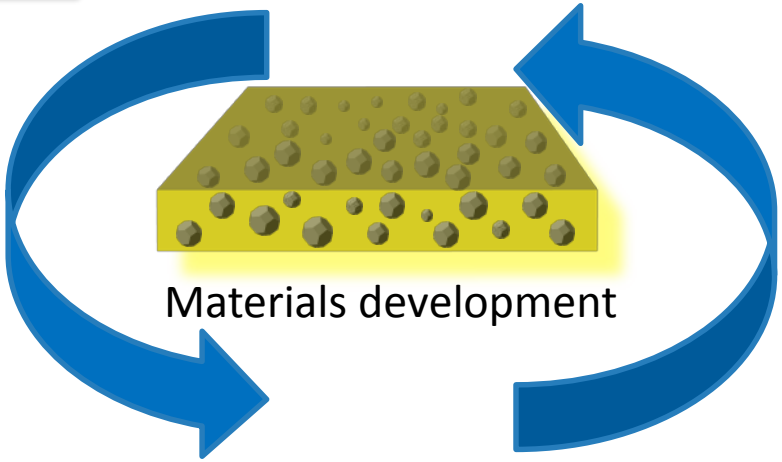


Membrane Fabrication



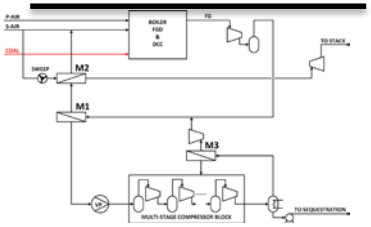
Molecular Design & Optimization



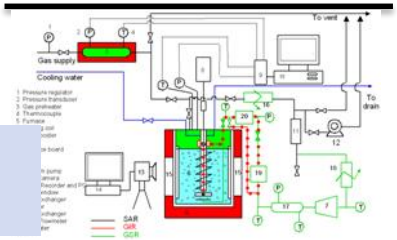


Characterization

Techno-Economic Analysis



Performance Evaluation



Multi-disciplinary research effort. Coordinated to accelerated development

Carbon Capture Simulation Initiative: CCSI
Accelerating Technology Development

CCSI
Carbon Capture Simulation Initiative

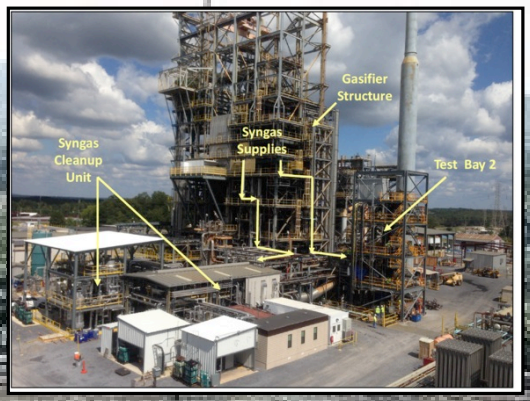
- **Develop new computational tools and models for industry**
  - Base development on industry needs/constraints
- **Demonstrate the capabilities of the CCSI Toolset on non-proprietary case studies**
  - Examples of how new capabilities improve ability to develop capture technology
- **Deploy the CCSI Toolset to industry**
  - T&E licenses, CRADA
  - Commercialization activities
- **Work with industry partners on pilot projects**
  - Ensure success & maximize learning at this scale
    - Data collection & experimental design
    - Develop & Validate models
    - UQ to identify critical data
  - Develop demonstration plant design
    - Utilize optimization tools (OUU, Heat Integration)
    - Quantitative confidence on predicted performance
    - Predict dynamic performance

CCSI^2
Carbon Capture Simulation for Industry Impact

NETL · Berkeley Lab · Lawrence Livermore National Laboratory · Los Alamos National Laboratory · Pacific Northwest National Laboratory · Carnegie Mellon · West Virginia University · Princeton University · Boston University · The University of Texas at Austin

National Carbon Capture Center

Pilot Solvent Test Unit



TRIG Gasifier

- 5 year $150MM
- $100MM Capture Funding
- Independent Test Facility
- Supports Capture & Gasification

Post-Combustion

- ❑ PC4 Facility – 4.3 MWe
- ❑ Real PC flue gas
- ❑ Bench through pilot scale
- ❑ ~44,000 hours of testing
- ❑ 29 technologies tested
- ❑ "Tech-Flexible"

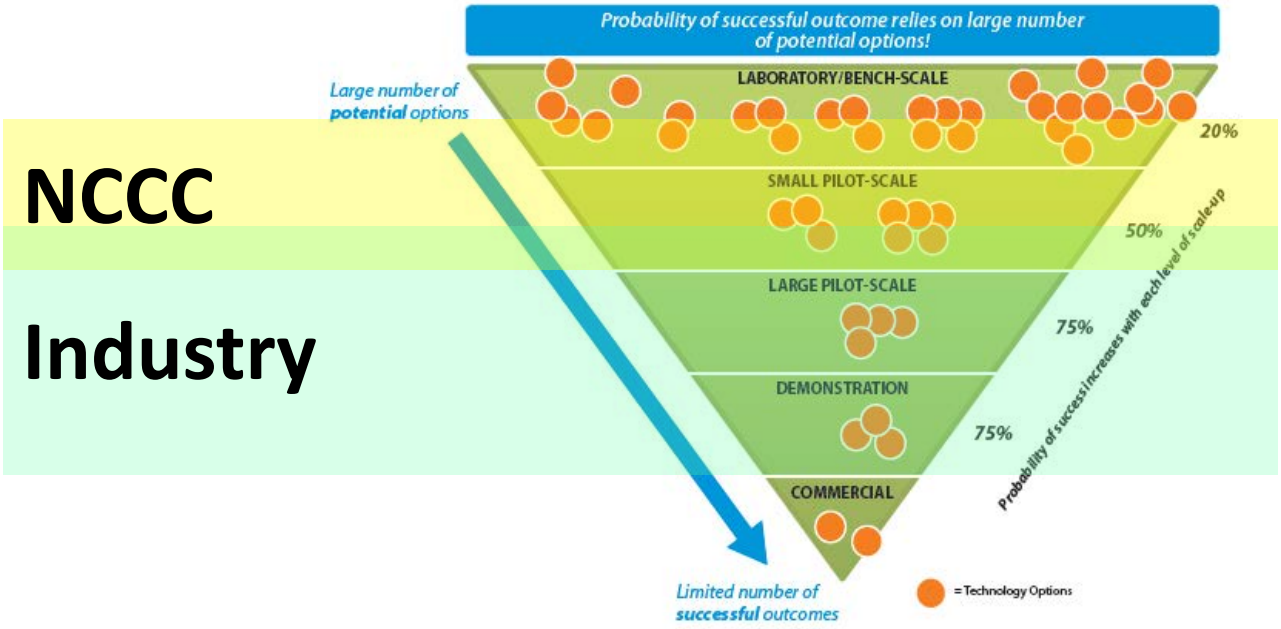
Pre-Combustion

- ❑ 6.3 MWe TRIG gasifier
- ❑ Air- or O_2 fired syngas
- ❑ Bench through pilot scale
- ❑ ~65,000 hours of testing
- ❑ 15 gasifier runs
- ❑ "Tech-Flexible"

– World Class Carbon Capture Technology Test Facility –

National Carbon Capture Center

Offering a **world-class neutral** test facility and a highly specialized staff, to **accelerate the commercialization** of advanced technologies and enable coal based power plants to achieve **near-zero emissions** (low cost CO_2).



2nd Generation
Small Pilot Scale Capture Plants

- **Technology scale-up is ongoing with pilot projects installed, undergoing shake down operations or testing on actual flue gas/syngas**

Carbon Capture Small Pilot Projects

Performer	Project Focus	Scale	Cost	Construction
	Post-Combustion Solvents (5)			
Linde, LLC	Slipstream Novel Amine-Based Post-Combustion Process	1 MWe	$22.7M	Complete
Neumann Systems Group, Inc	Carbon Absorber Retrofit Equipment	0.5 MWe	$9.2M	Complete
University of Kentucky	Heat Integrated Post-combustion CO_2 Capture System Using the MHPSA Advanced Solvent	0.7 MWe	$21.4M	Complete
General Electric	Novel Aminosilicone Solvent	0.5 MWe	$6.3M	Complete
ION Engineering	Amine Solvent in Ionic Liquid	0.7 MWe	$10.9M	Complete
	Post-Combustion Sorbents (3)			
ADA-Environmental Solutions	Solid Sorbents as Retrofit Technology	1 MWe	$24.3M	Complete
TDA Research, Inc.	Alkalized Alumina Solid Sorbent	0.5 MWe	$5.9M	Late 2016
SRI International	Novel Solid Sorbent	1 MWe	$12.9M	Late 2016
	Post-Combustion Membranes (3)			
Membrane Technology & Research	Polymeric Membranes	1 MWe	$18.8M	Complete
Gas Technology Institute	Hollow-Fiber-Membrane Contactor with aMDEA Solvent	0.5 MWe	$12.8M	Late 2016
FuelCell Energy Inc.	Combined Electric Power and CO_2 Separation (CEPACS) System	3 MWe	$23.7M	TBD
	Pre-Combustion (2)			
SRI International	CO2 Capture Using AC-ABC Process	0.1 MWe	$6.1M	Complete
TDA, Inc.	High Capacity Regenerable Sorbent	0.1 MWe	$9.9M	Late 2016

FY2015 Funding Opportunity Announcement
Large Scale CO_2 Capture Projects (10+ MWe)

- **Need several pilots to support 2025 target for 2nd Generation technology demonstrations**
- **Necessary for:**
  - Validation of capture technology
  - Integration of advanced capture system components
  - Optimization of capture system for full scale demo
- **Phase I – Design (6 awards) (2015-2016)**
  - Selections Made
- **Phase II – Construction and operations (2016-2020)**
  - Phase I Projects have submitted their Phase II Applications
  - Applications being reviewed

Large Scale Post-Combustion Pilots –Phase I

- **General Electric –** Aminosilicone capture process, 10 MWe+
- **University of Illinois -** Linde/BASF CO_2 capture technology at the Abbott coal-fired power plant, 25 MWe
- **University of Kentucky –** Heat integrated capture system, 10 MWe+
- **Southern Company Services –** Process improvements/advanced solvent at Plant Barry Pilot Facility, 25 Mwe
- **Alstom Power –** Improvements to chilled ammonia process, 15 Mwe
- **NRG CO_2NCEPT–** VeloxoTherm™ solid sorbent capture system, 10 MWe

Lessons Learned

- **Communication is essential and required throughout project**
- **Involve ALL stakeholders early and often**
- **Scope definition with vendors, fabricators, construction contractors and project partners upfront is critical**
- **Include performance acceptance testing for equipment and pilot unit.**
  - At OEM/Fabricator site as well as host test site on actual gas
- **Confirm that host site, state, local codes, standards and procedures are well understood by all parties, since interpretations may differ.**
- **Review designs in great detail with:**
  - host site, safety personnel, fabricator, engineers, and technology developer for potential issues early and often
- **Expect unknowns will occur. Have a procedure for addressing them**
- **Delays will occur. So plan for them to avoid critical path efforts that jeopardize the schedule and/or budget**

MAINTAIN A GOOD WORKING RELATIONSHIP

For More Information About the NETL Carbon Capture Program

NETL
www.netl.doe.gov

facebook.com/FossilEnergy

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José D. Figueroa
Carbon Capture Coordinator,
Carbon Capture Team
U. S. Department of Energy
National Energy Technology Laboratory
(Tel) 412 386-4966
Jose.Figueroa@netl.doe.gov

Lynn Brickett
Portfolio Manager
Carbon Capture Program
U. S. Department of Energy
National Energy Technology Laboratory
(Tel) 412-386-6574
Lynn.Brickett@netl.doe.gov