Santa Fe Institute
Summer School on Global Sustainability

Technology and Implications for Sustainability

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Outline

- Summary thoughts from the first lecture
- Fundamentals
- Technology opportunities
- The next wave
- Closing thoughts
- Q&A

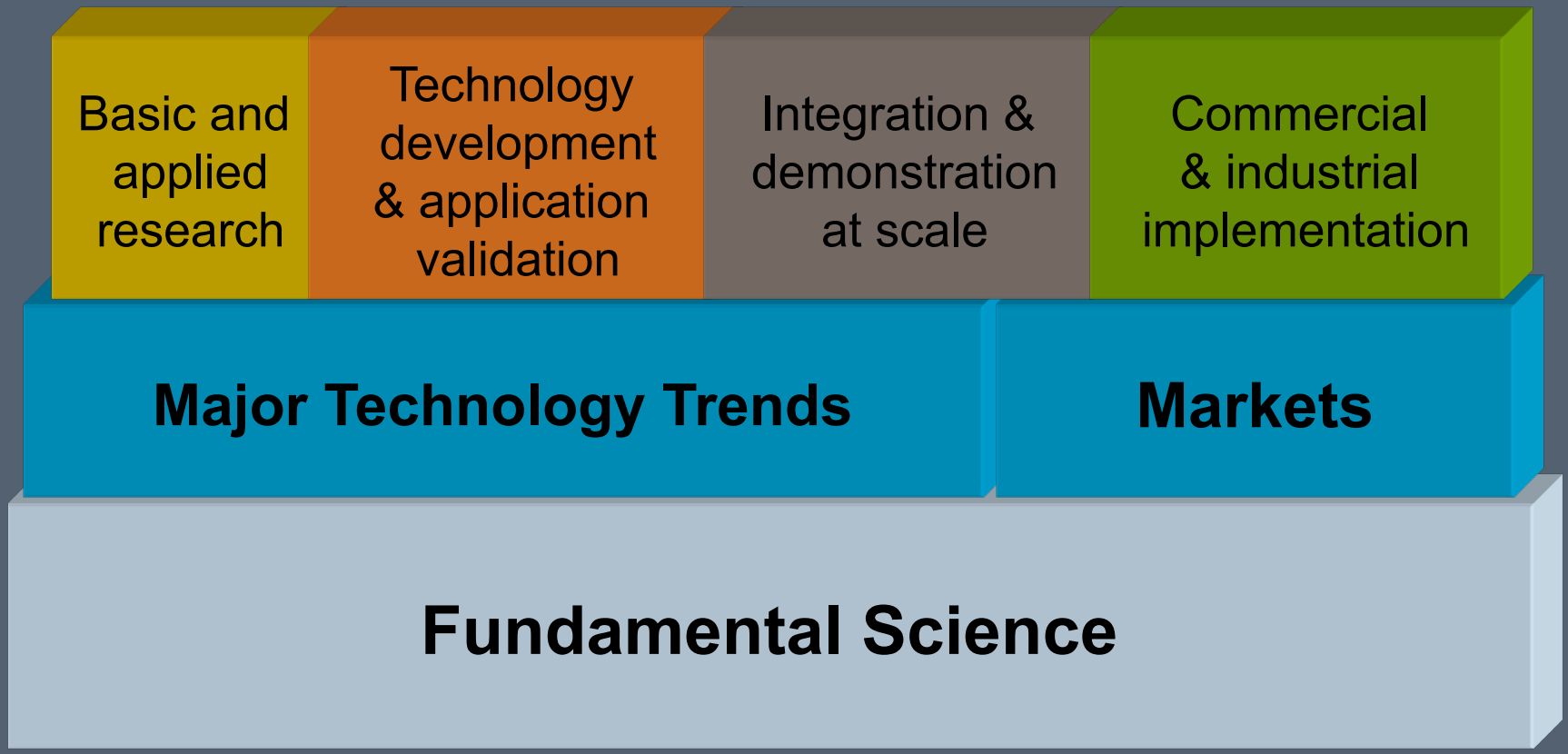
Global energy system

- Complexity: technology + business + policy
- Scale: “1% matters”
- Time: history, the present, and the future co-exist
- Global demand growth will continue – dominated by the developing economies
- Fossil energy will continue to be a primary source – conventional supplies will peak in the coming decades
- Diversification will be an expanding component – transition effects will be important
- Carbon management at scale - requires a solution for coal

Fundamentals

- Structure
- Participants
- Major trends intersect energy
- Opportunities pull development

Structure


Basic and applied research
Technology development & application validation
Integration & demonstration at scale
Commercial & industrial implementation
Major Technology Trends
Markets
Fundamental Science

Structure

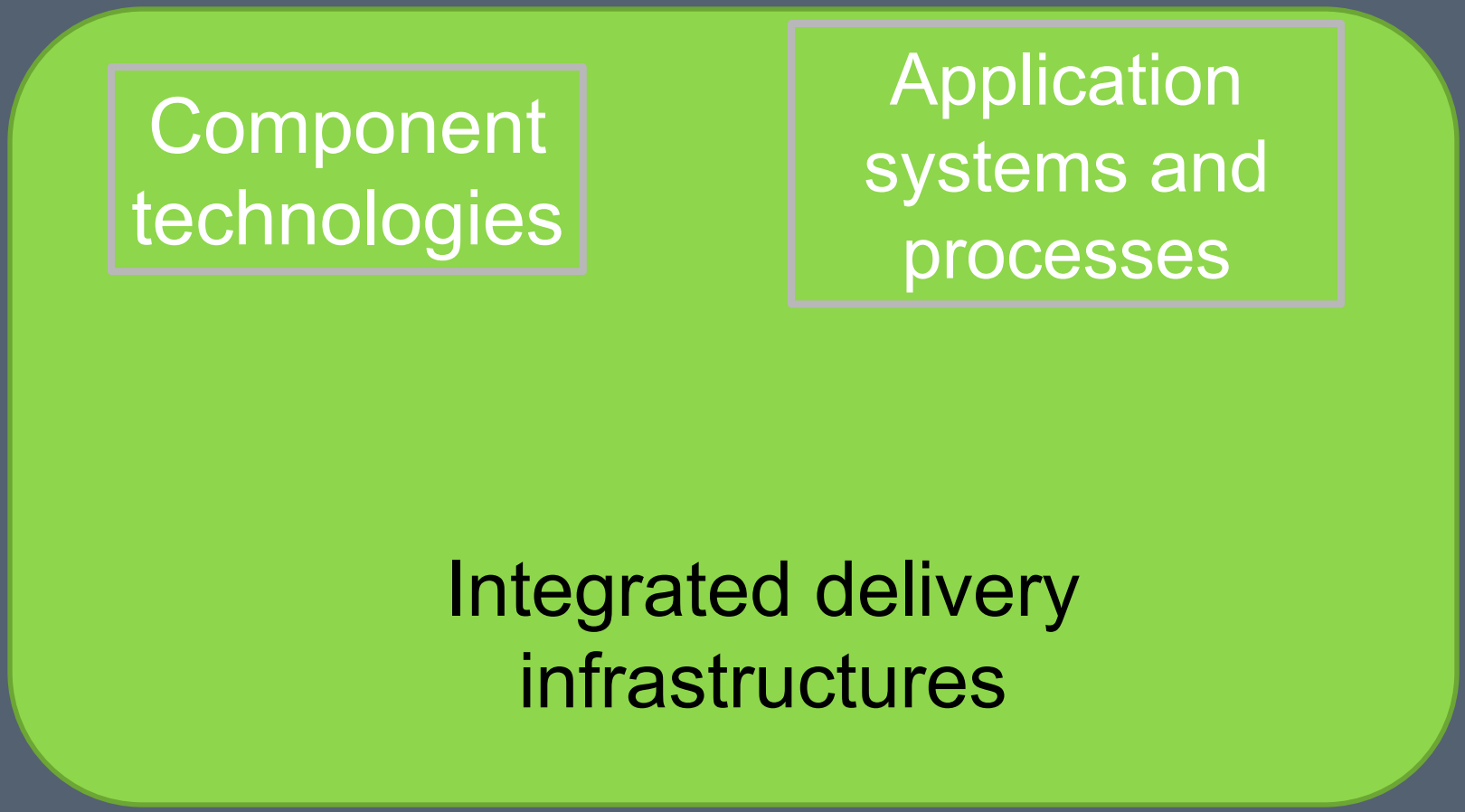
Component technologies

Structure

Component technologies

Application systems and processes

Structure


Component technologies
Application systems and processes
Integrated delivery infrastructures

Structure: components, systems, and infrastructure

Diverse participants in the system

- Governments
  - Funding agencies
  - National laboratories
  - Defense and security installations
- Universities
- Non-profit research institutes
- Industrial and technology companies
- Venture capital and private equity investors
- Emerging technology companies

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Tech Transfer Challenge:
Alignment of interests
- motivations
- business models
- time frames
- cultures

Major technology trends intersecting energy

- Growing digital intensity
- Molecular transformation technology
- Advanced materials

Growing digital intensity

- Moore's law
- Universal digitization- the data tidal wave
- Next-gen connectivity
- Human-digital and social-digital relationships
- Real-world robotics

Molecular transformation technology

- "Converts what you have to what you want"
- Both biological and thermo-chemical
- Synthetic fuels, lubricants, and chemicals
- Use CO2 as a feedstock?

Opportunities pull technology development

- Improving economic performance of existing supply chains and systems
- Extending existing resources / adding new resources / substituting resources
- Diversifying demand options
- Managing carbon at scale

Some specific opportunities

- “Digital Energy” – electron convergence

Digital Energy

- Opportunity drivers:
  - Supply chain efficiency and economic performance
  - Diversity the power grid
  - Manage increased complexity and variability
  - Create new infrastructure and energy use paradigms
- Technology enablers:
  - Exponential growth in digital technology and data

Digital Energy: “Smart Grids”

- Directly couples the world’s largest infrastructure systems
- Rides on the IT growth curve in sensing, digitization, and connectivity
- Creates large potential for efficiency gains and integration of highly-variable power sources
- Creates a system of unprecedented complexity and scale

Evolution and diversification of the power grid

"Smart Grids"

WIND & SOLAR

Distributed Generation

NATURAL GAS

BASELOAD

Carbon Management

Energy productivity

Some specific opportunities

- “Digital Energy” – electron convergence
- Fuel feedstock diversification

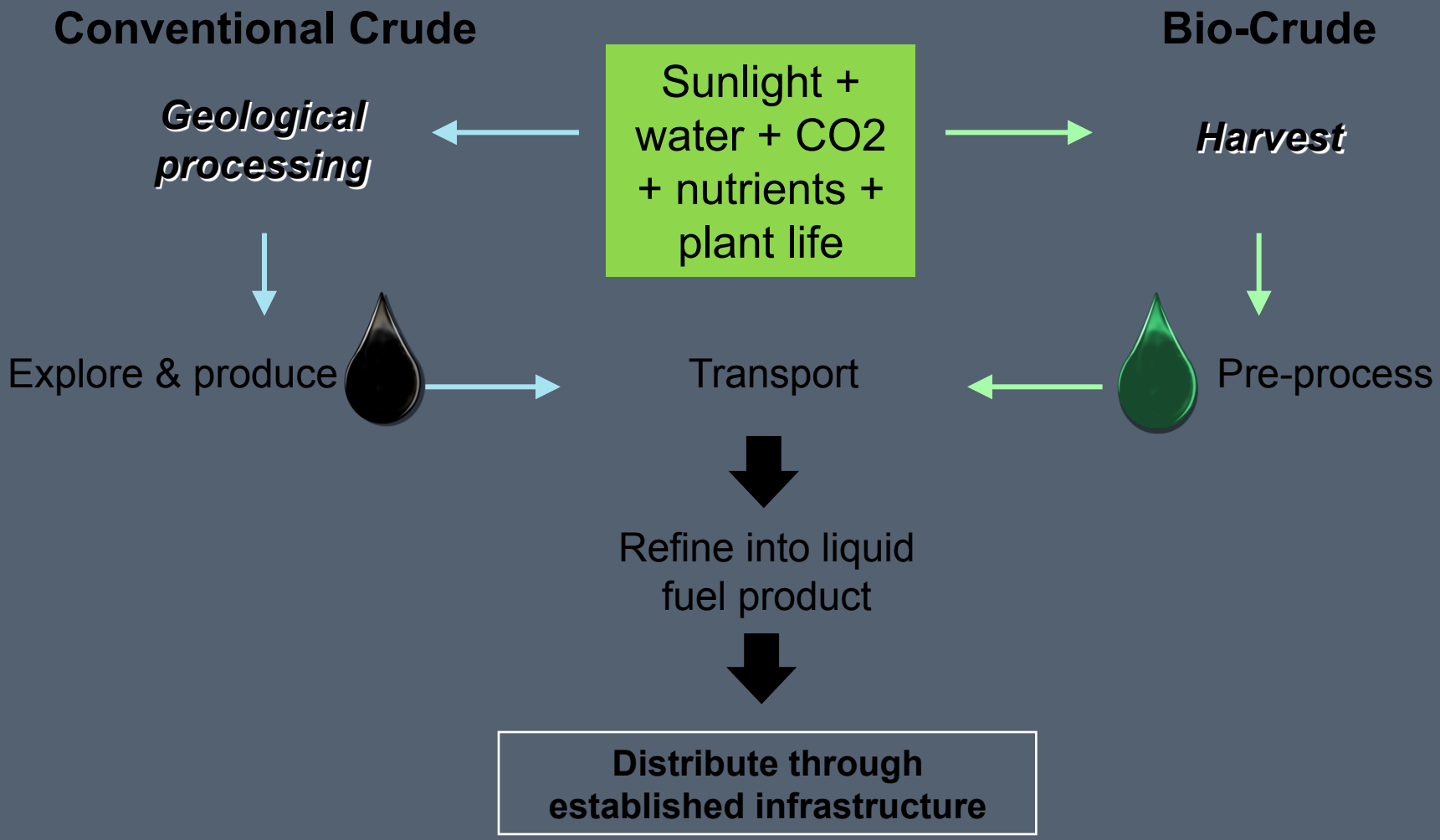
Fuel feedstock diversification

- Opportunity drivers:
  - Conventional petroleum supply will peak eventually
  - Potentially enormous new feedstock sources exist
  - Low-carbon Fuel Standards emerging
  - Changes to the auto-mobility paradigm
  - Geopolitical factors
- Technology enablers:
  - Digital technologies
  - Molecular transformation technologies
  - Carbon management technologies

Continued advances in natural resource technologies

- Advanced subsurface imaging and geological characterization
- Precision well engineering and control
- Engineered reservoirs
- Extended operational systems
- Advanced materials and robotic production systems

Renewable fuels: next generation technology and new business models for scale



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Some specific opportunities

- “Digital Energy” – electron convergence
- Fuel feedstock diversification
- Green supply chains / super-efficient use

Green supply chains / super-efficiency

- Opportunity drivers:
  - regulatory standards,
  - improved capital efficiency
  - lower operating costs
  - expanded markets
- Enabling technologies:
  - Universal digitization
  - Advanced materials and manufacturing
  - Re-use transformation technologies

Some specific opportunities

- “Digital Energy” – electron convergence
- Fuel feedstock diversification – every molecule counts
- Green supply chains / super-efficient use
- De-carbonization of coal

De-carbonization of coal

- Opportunity drivers:
  - Carbon regulation
  - Large installed base and huge resource
  - Synthetic fuels for diversification
- Enabling technologies:
  - Conversion / transformation technologies
  - Separation and purification technologies
  - Adaptation of O&G subsurface technologies

What's next?

- Electricity storage at scale
- CO2 as a feedstock
- Resource switching
- New "consumers"

Technology and Sustainability

- Necessity and technical performance is not sufficient
- Substitution markets are much more difficult than growth markets
- Evolving the financial and business models for efficiency, renewable sources, and resource switching

Closing thoughts…

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- Technological intensity and complexity are increasing
- Continued technology development can be expected
- Fundamental advances will create new technology platforms
- Deployment at scale will take time and significant resources
- An expanded and diversified effort is critical to meeting both economic and sustainability objectives

Questions?