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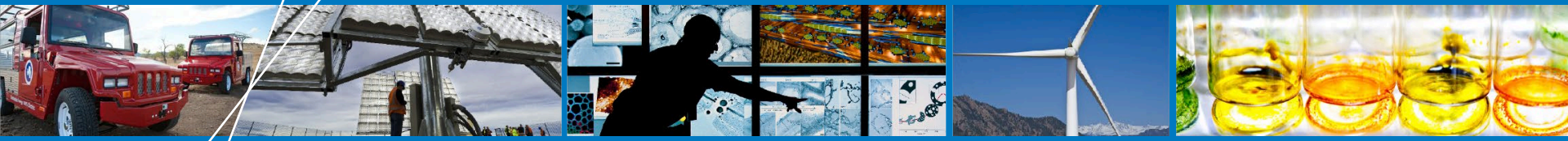
# Dynamic Modeling of Learning in Emerging Energy Industries:

# The Example of Advanced Biofuels in the United States



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Cambridge, Massachusetts

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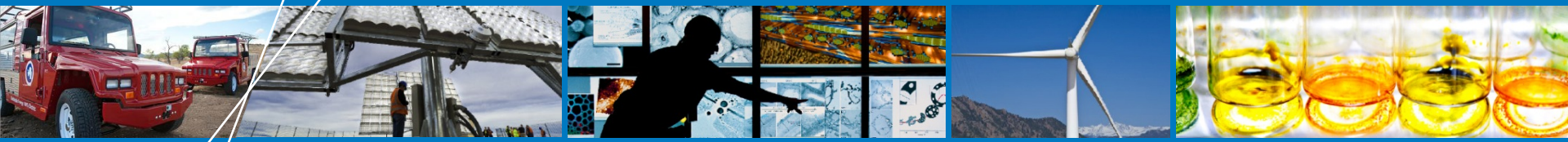
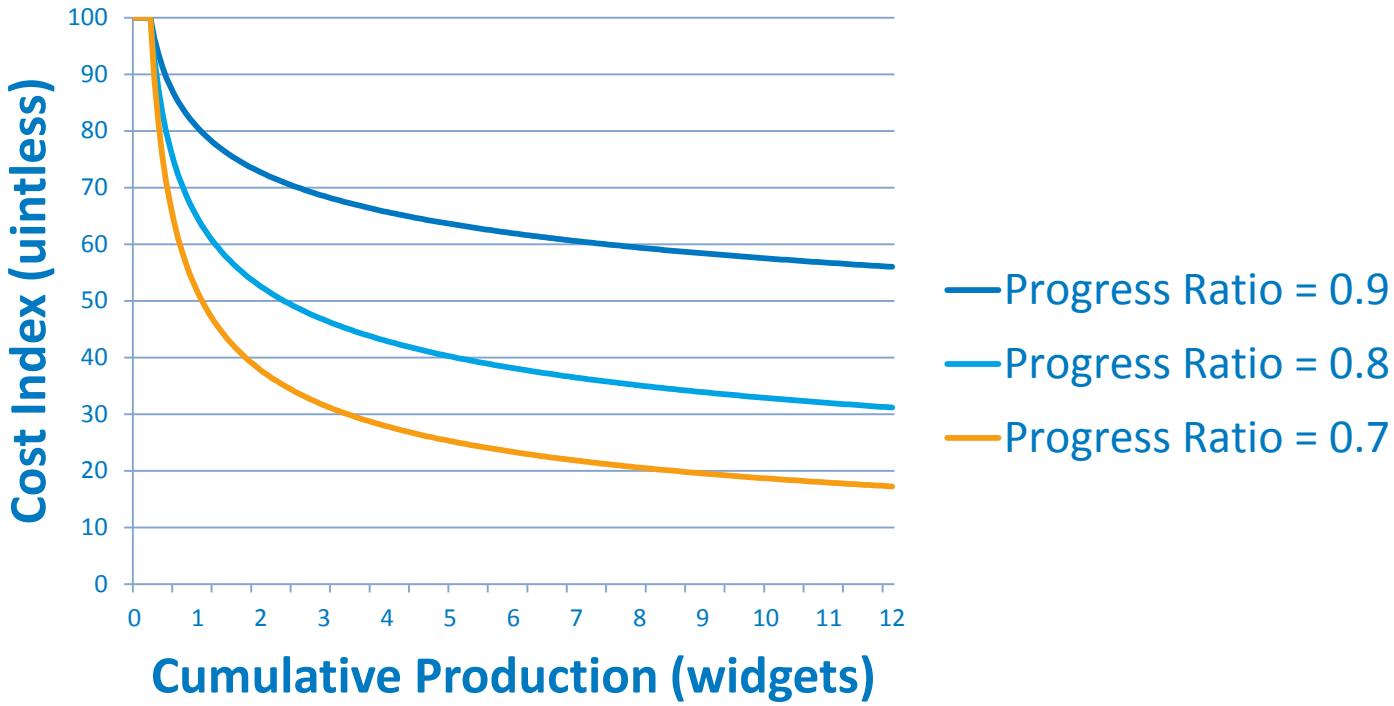


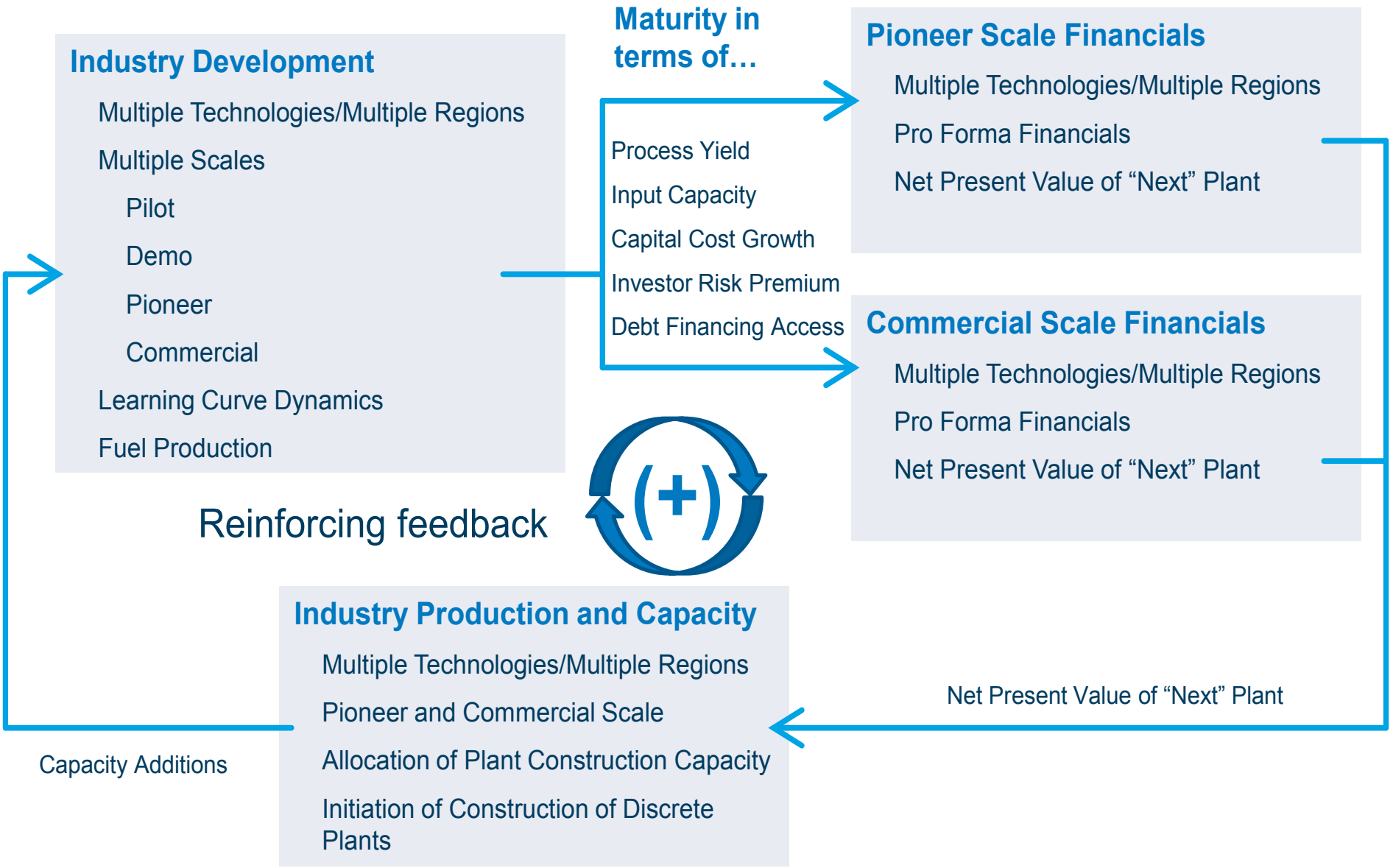
# Introduction to the Learning Model

# What is industrial learning?

- Production cost reduction as a function of cumulative production volume (observed and assumed)
- Research distinguishes among different types of learning
- Quantitative metric is progress ratio, the relative cost after each doubling of cumulative production

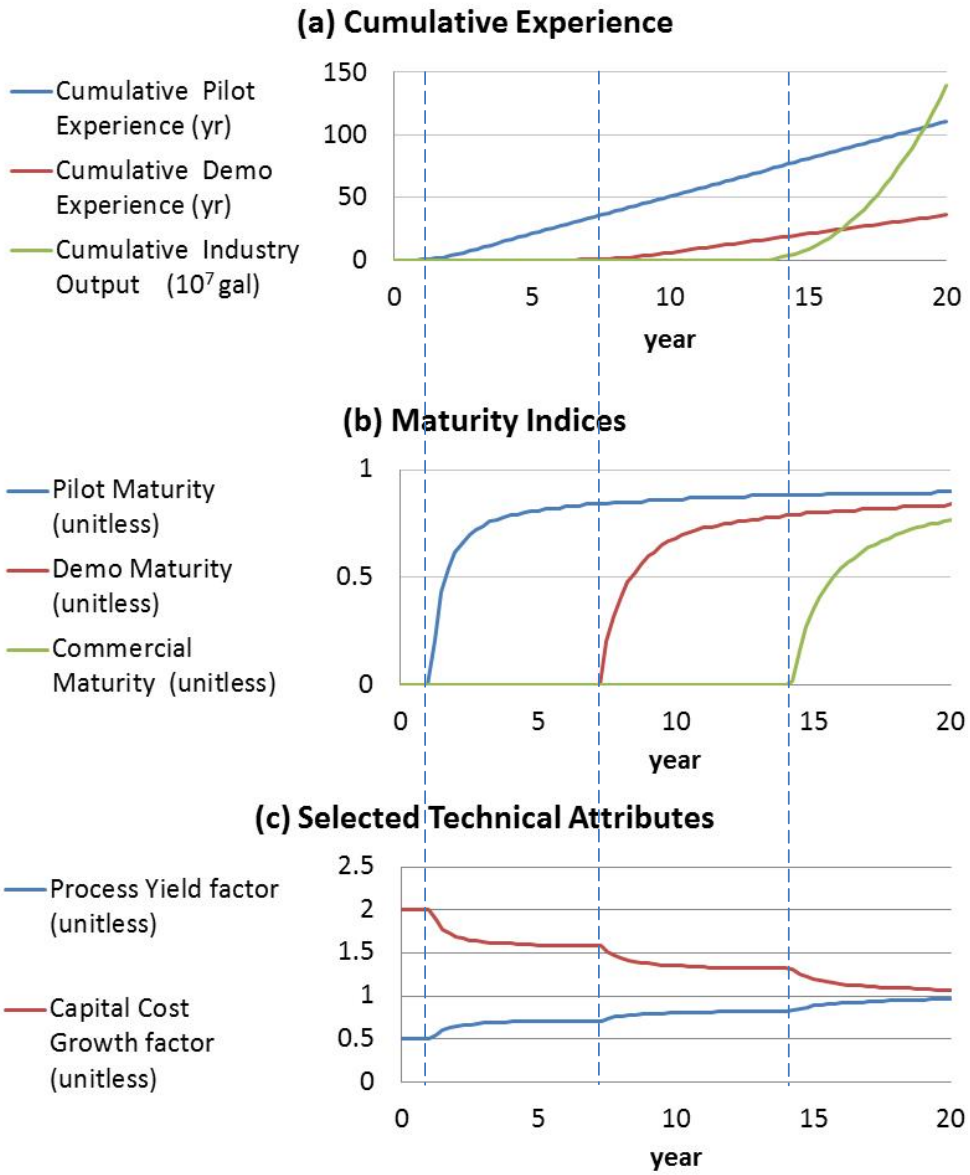


# Technology development, finance, and production are coupled



# Models use multiple stages in learning mechanism

- Learning Model (and BSM) divide technology development into pilot, demonstration, and commercial stages
- Experience accumulates with time (in pilot and demo) or production (commercial)
- Maturity and associated technical cost and performance metrics improve at each stage



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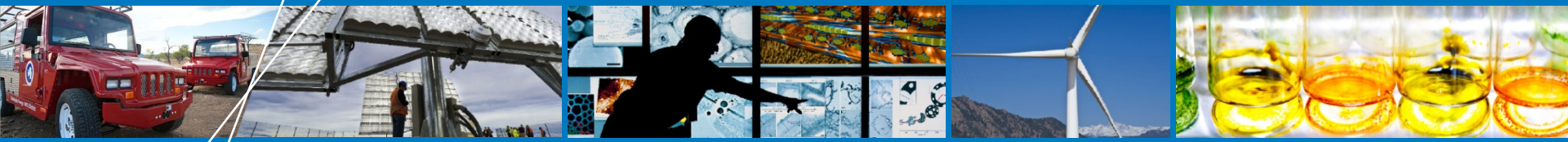
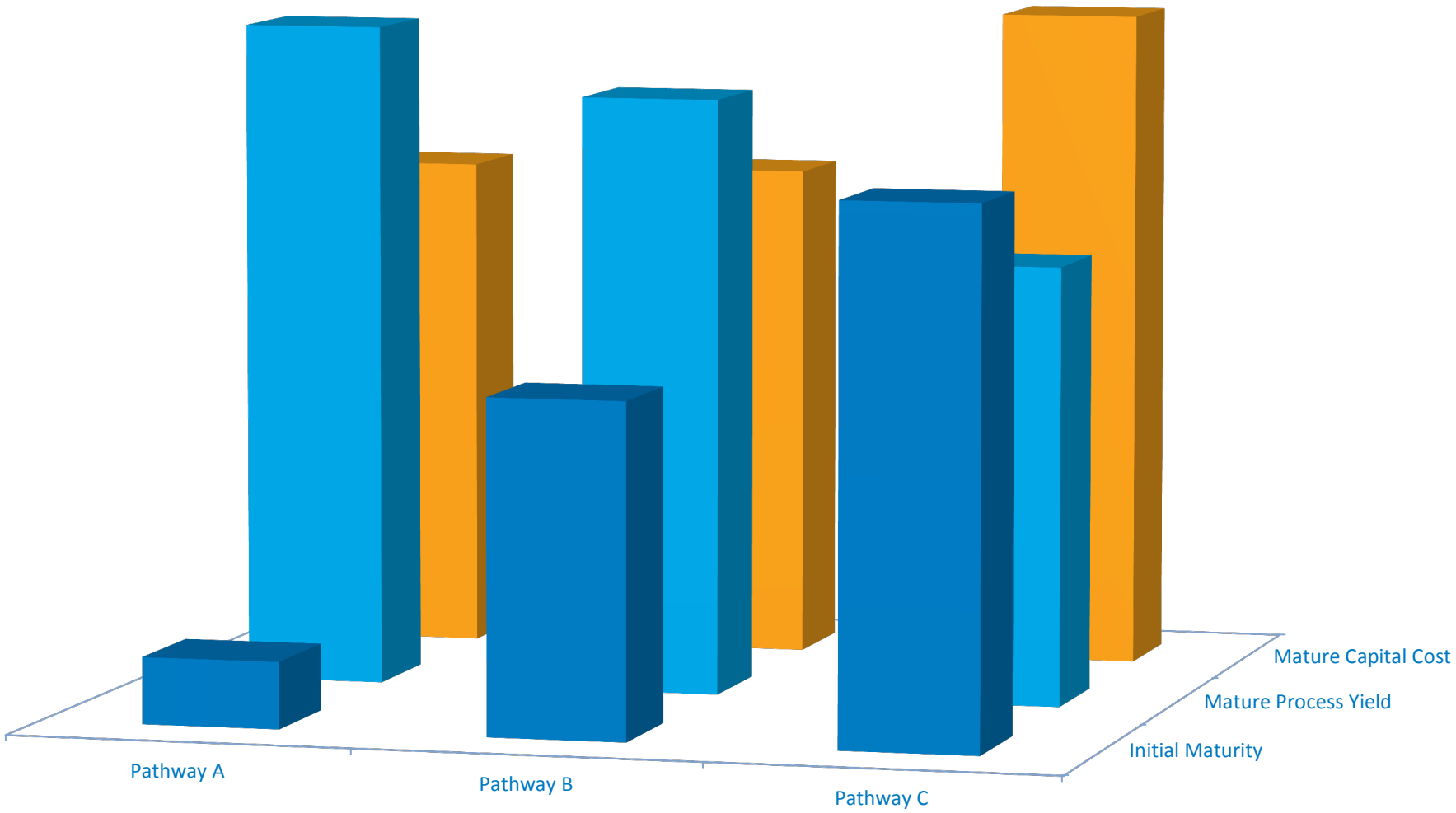


# Scenario Analysis of the Learning Model

# Comparison of three pathways with different technology cost and performance

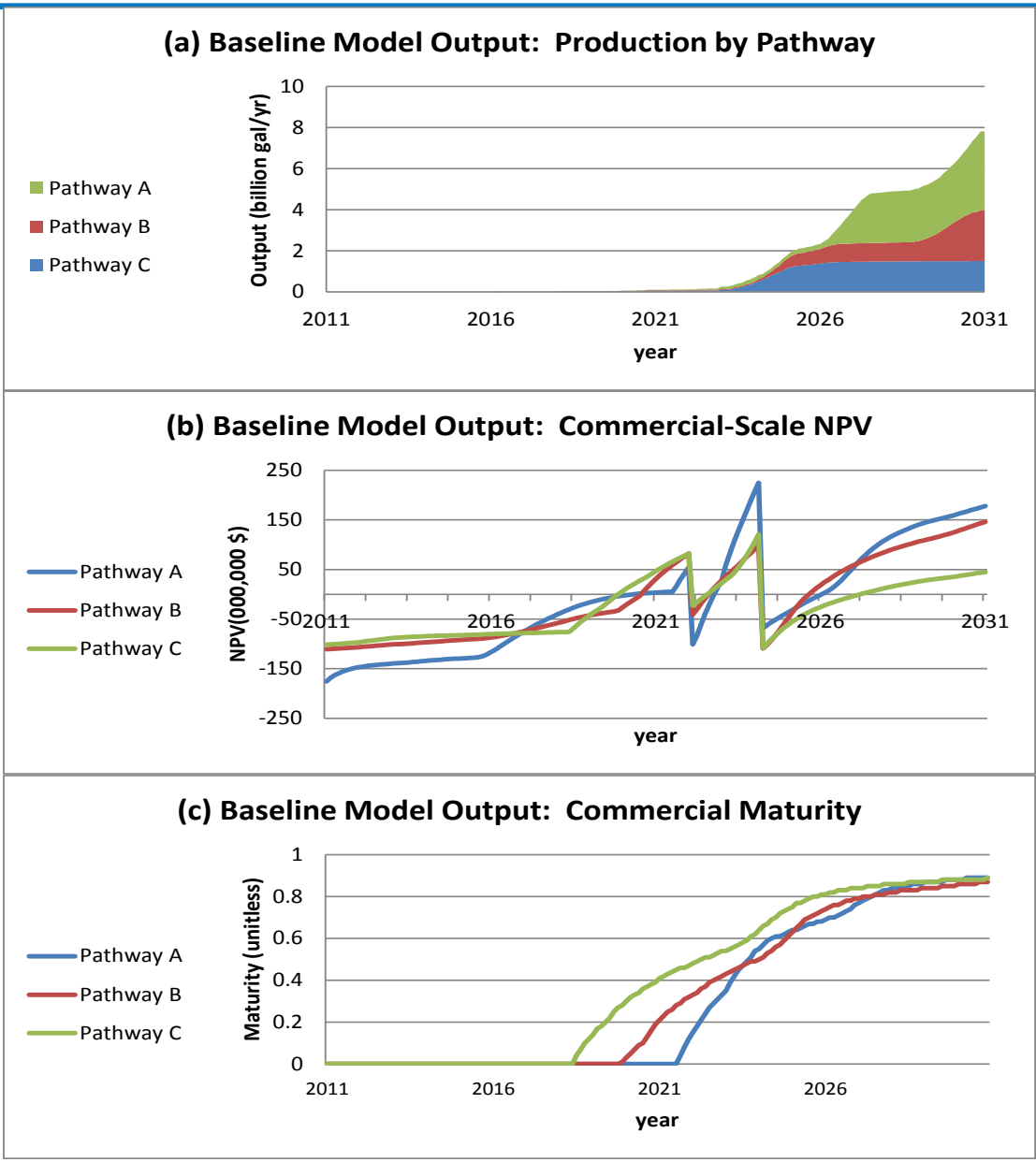
- Real-world biomass-to-biofuel conversion technology pathways vary in their relative
  - Maturity today
  - Expected process yield of a mature commercial biorefinery
  - Expected capital cost of a mature commercial biorefinery
- We performed a sensitivity analysis on cost and performance metrics

# Comparison of three pathways with different technology cost and performance



# Metrics show technology development, financial attractiveness, and production

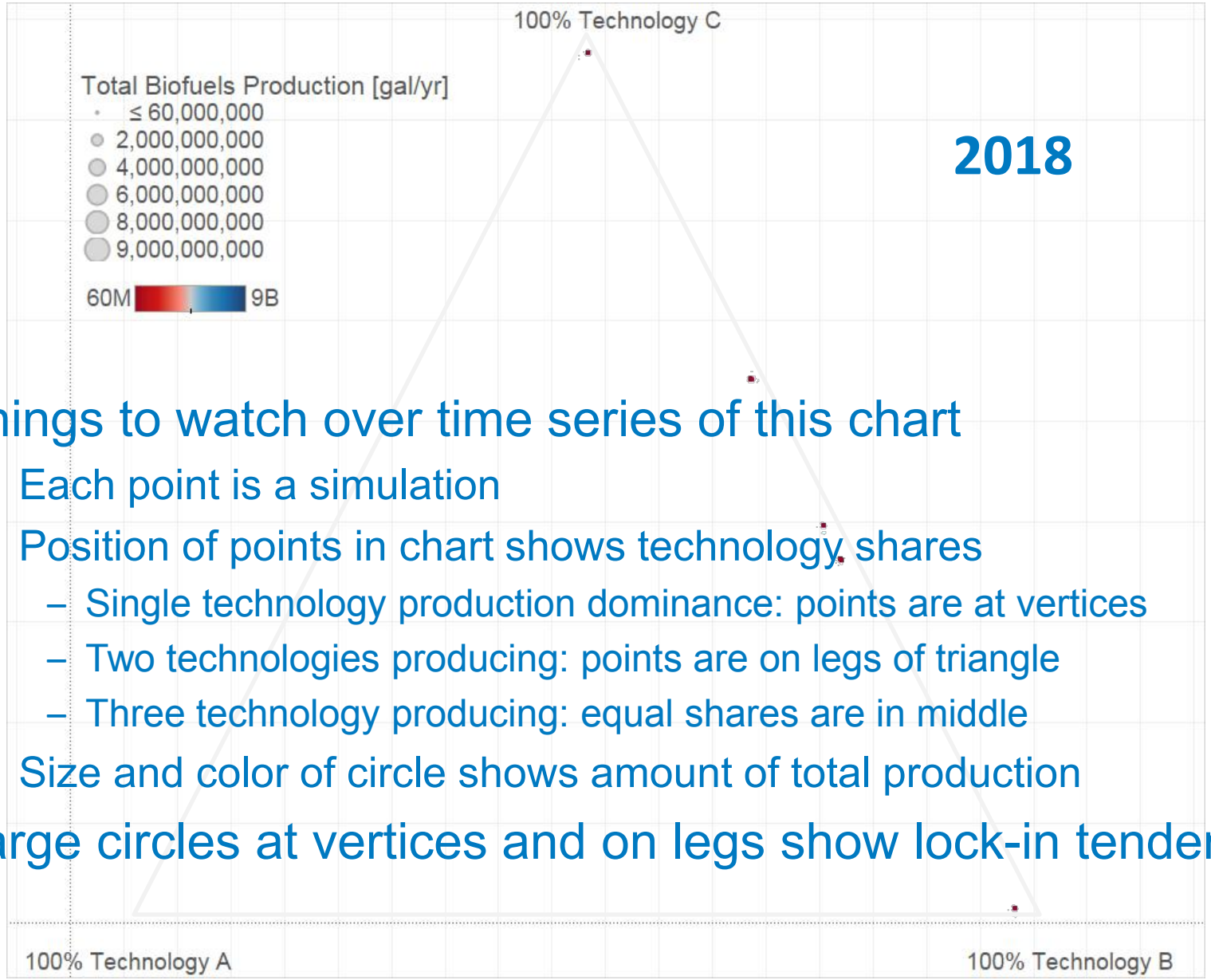
- Baseline set so that all three pathways grow
- Model shows possible features of transition to commercial production
  - Oscillations in NPV reflect expiring subsidies
  - Relative production shares indicate potential for early technologies to plateau



# Sensitivity analysis explores effects of pathway inputs through all combinations of selected variations

| | | Pathway A Baseline | Pathway B Baseline | Pathway C Baseline | Sensitivity Variation |
|---|---|---|---|---|---|
| **Mature Industry Techno-economics** | Feedstock Input (dry short ton/day) | 2,000 | 2,000 | 2,000 | |
| | Fixed Capital Investment ($) | 300,000,000 | 300,000,000 | 400,000,000 | 1.15 x baseline |
| | Fixed Operating Cost ($/yr) | 15,000,000 | 15,000,000 | 15,000,000 | |
| | Other (non-feedstock) Variable Operating Cost ($/yr) | 50,000,000 | 40,000,000 | 5,000,000 | |
| | Co-Product Sales Revenue ($/yr) | 5,000,000 | 16,000,000 | 10,000,000 | |
| | Process Yield (gal/dry short ton) | 100 | 90 | 66 | 0.85 x baseline |
| **Initial Technical Maturity (unit-less)** | Pilot | 0.1 | 0.5 | 0.85 | 0.85 x baseline (pathway "B" only) |
| | Demonstration | 0 | 0.5 | 0.75 | |
| | Commercial | 0 | 0 | 0 | |
| **Progress Ratio (1/doubling)** | Pilot | 0.75 | 0.75 | 0.75 | 1.05 x baseline |
| | Demonstration | 0.75 | 0.75 | 0.75 | |
| | Commercial | 0.75 | 0.75 | 0.75 | |
| **Pre-Commercial Investment (projects/yr)** | Pilot | pre-2012: 2<br>2012: 4<br>2013: 4<br>2014: 4 | pre-2012: 2<br>2012: 4<br>2013: 4<br>2014: 4 | pre-2012: 2<br>other yrs: 0 | |
| | Demo | pre-2012: 0<br>2014: 4<br>2015: 4<br>2016: 4 | pre-2012: 0<br>2014: 4<br>2015: 4<br>2016: 4 | pre-2012: 0<br>other yrs: 0 | |

# Modeled system shows tendency for technology lock-in




- Things to watch over time series of this chart
  - Each point is a simulation
  - Position of points in chart shows technology shares
    - Single technology production dominance: points are at vertices
    - Two technologies producing: points are on legs of triangle
    - Three technology producing: equal shares are in middle
  - Size and color of circle shows amount of total production
- Large circles at vertices and on legs show lock-in tendency

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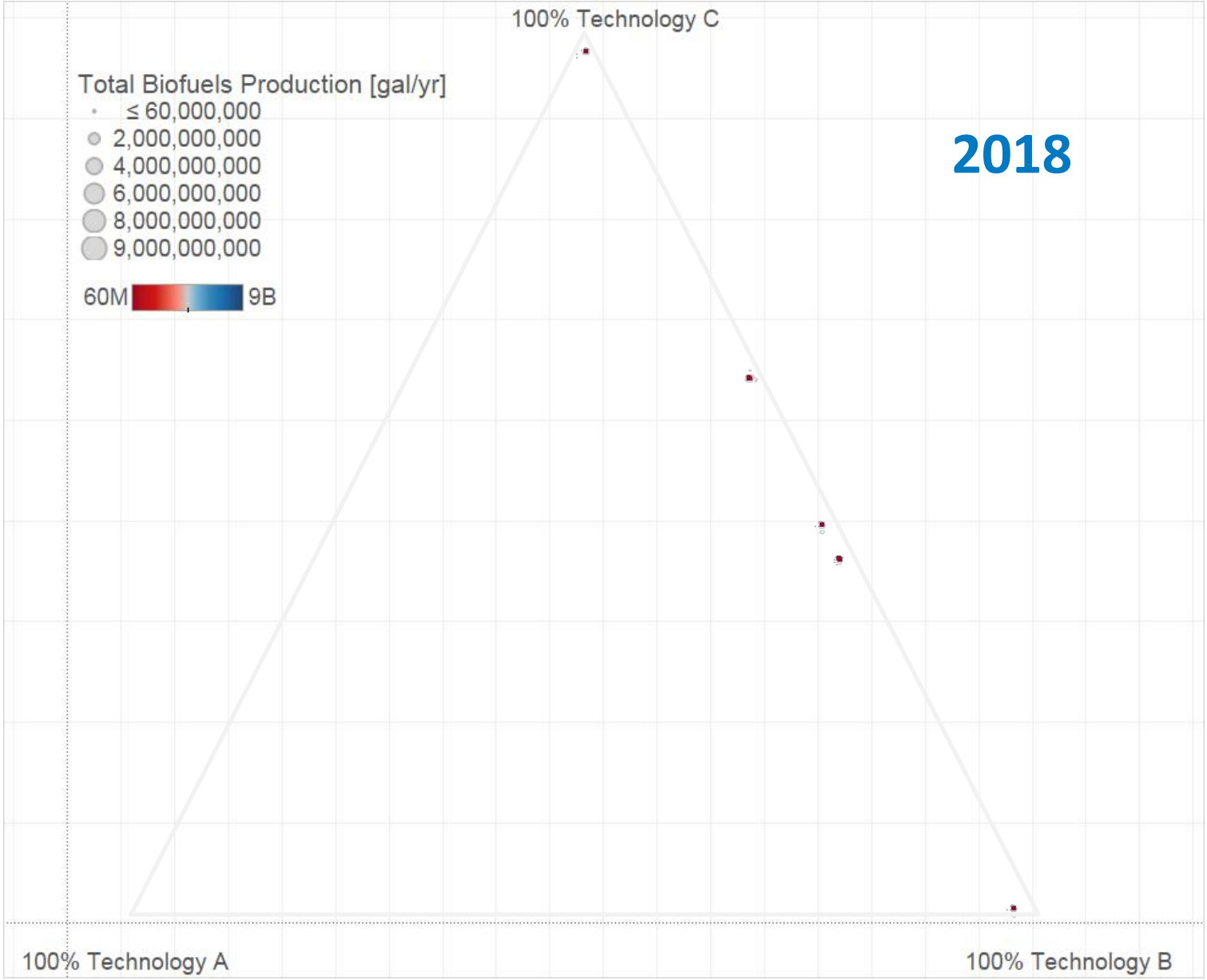
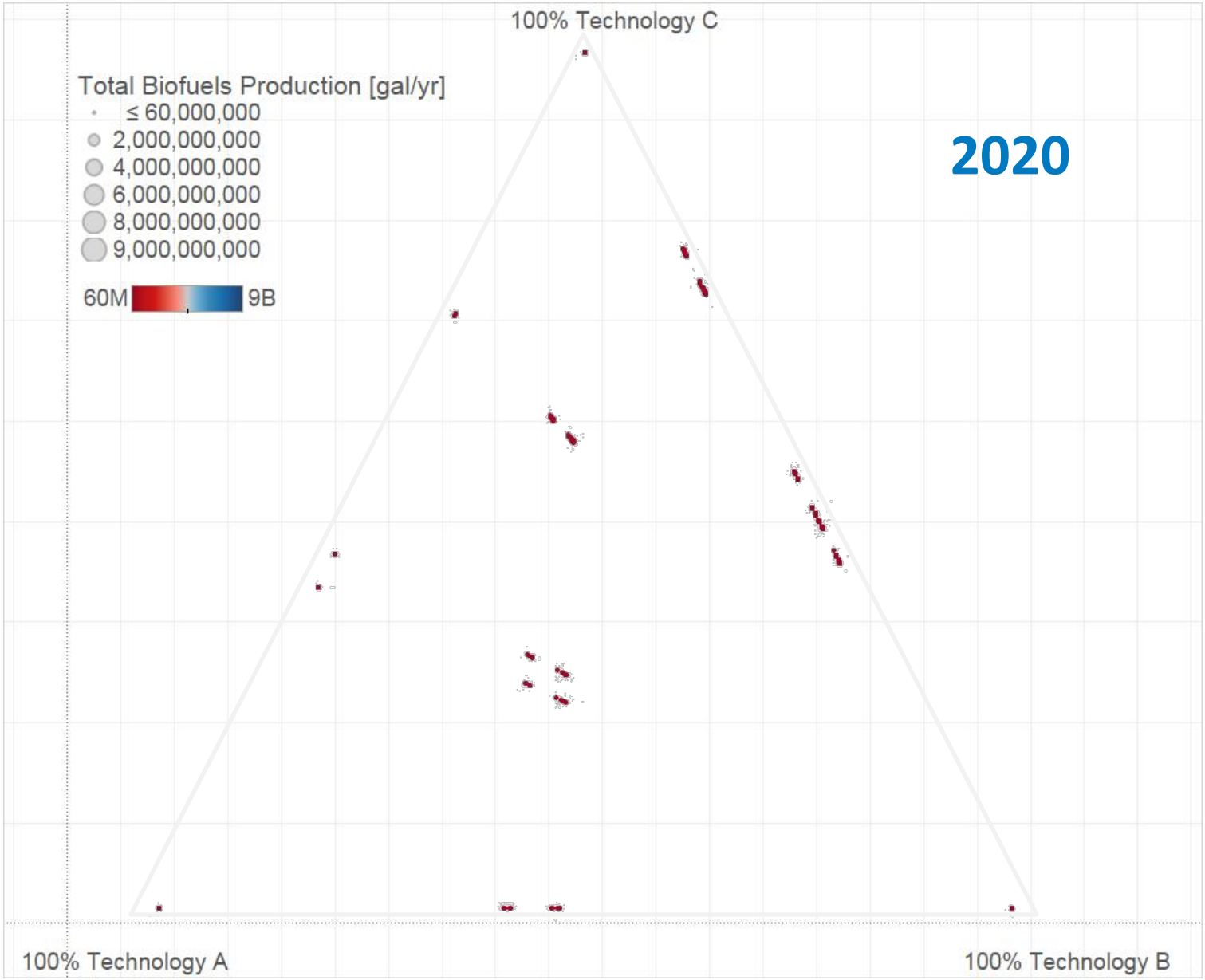


# Modeled system exhibits technology lock-in



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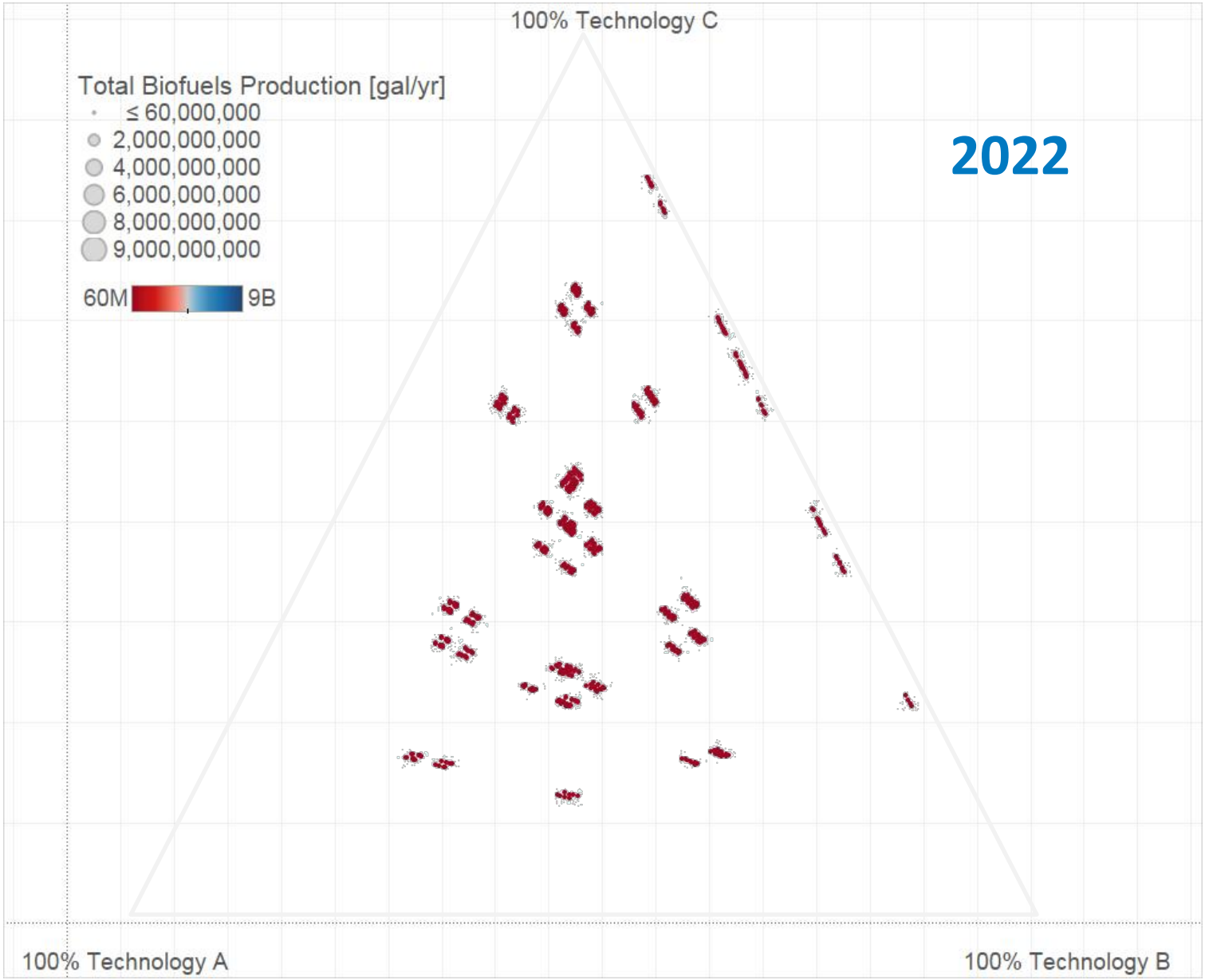

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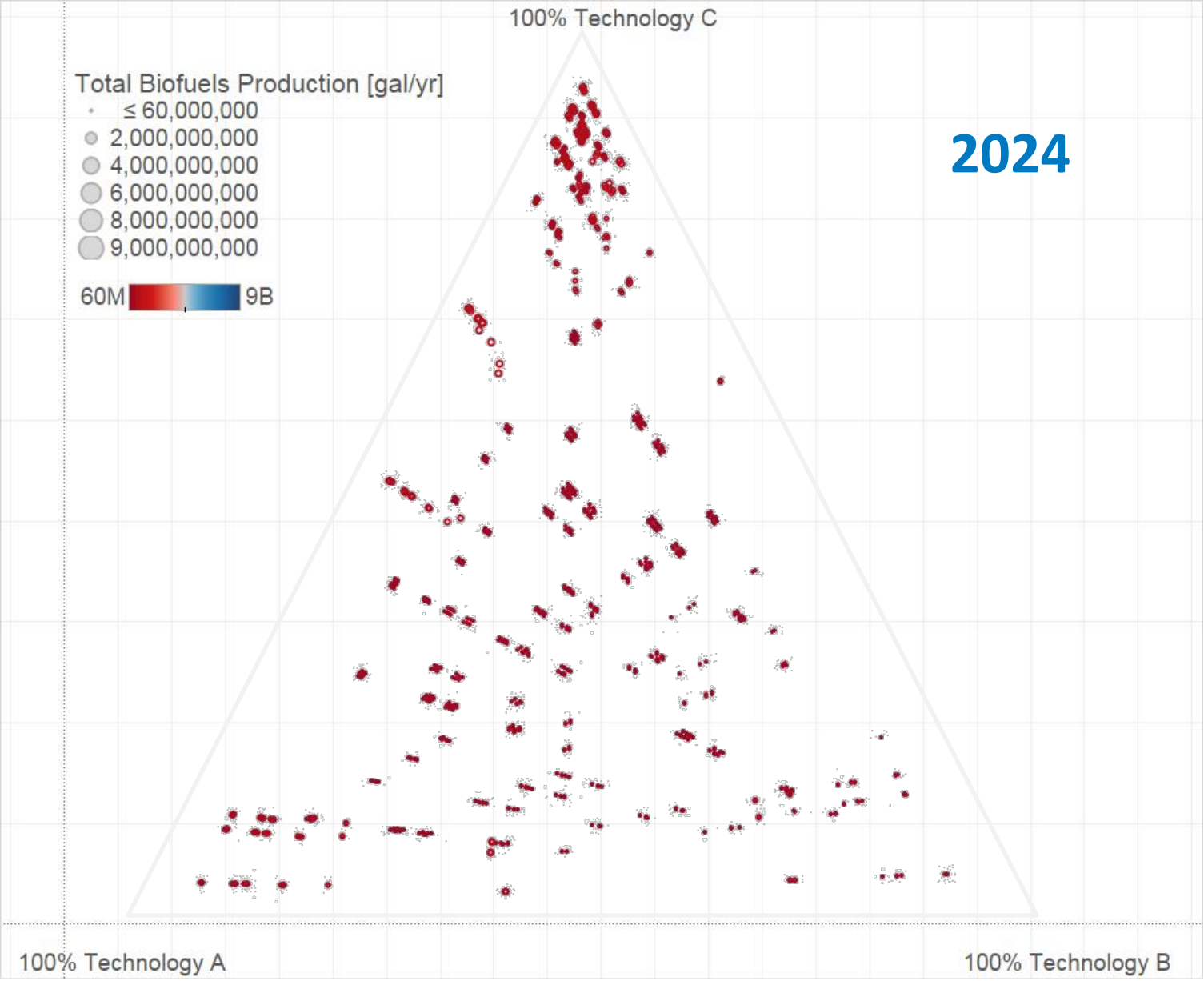

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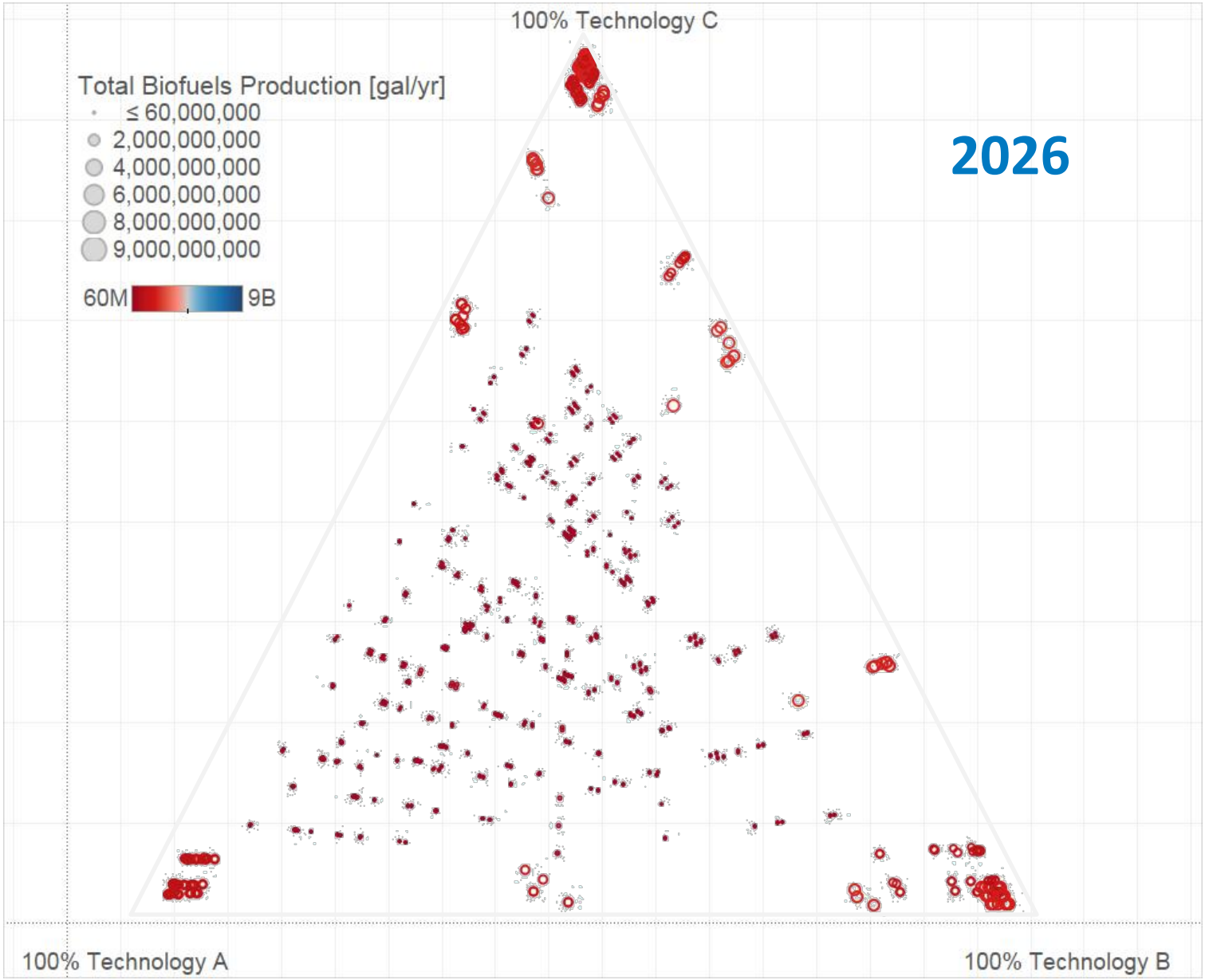

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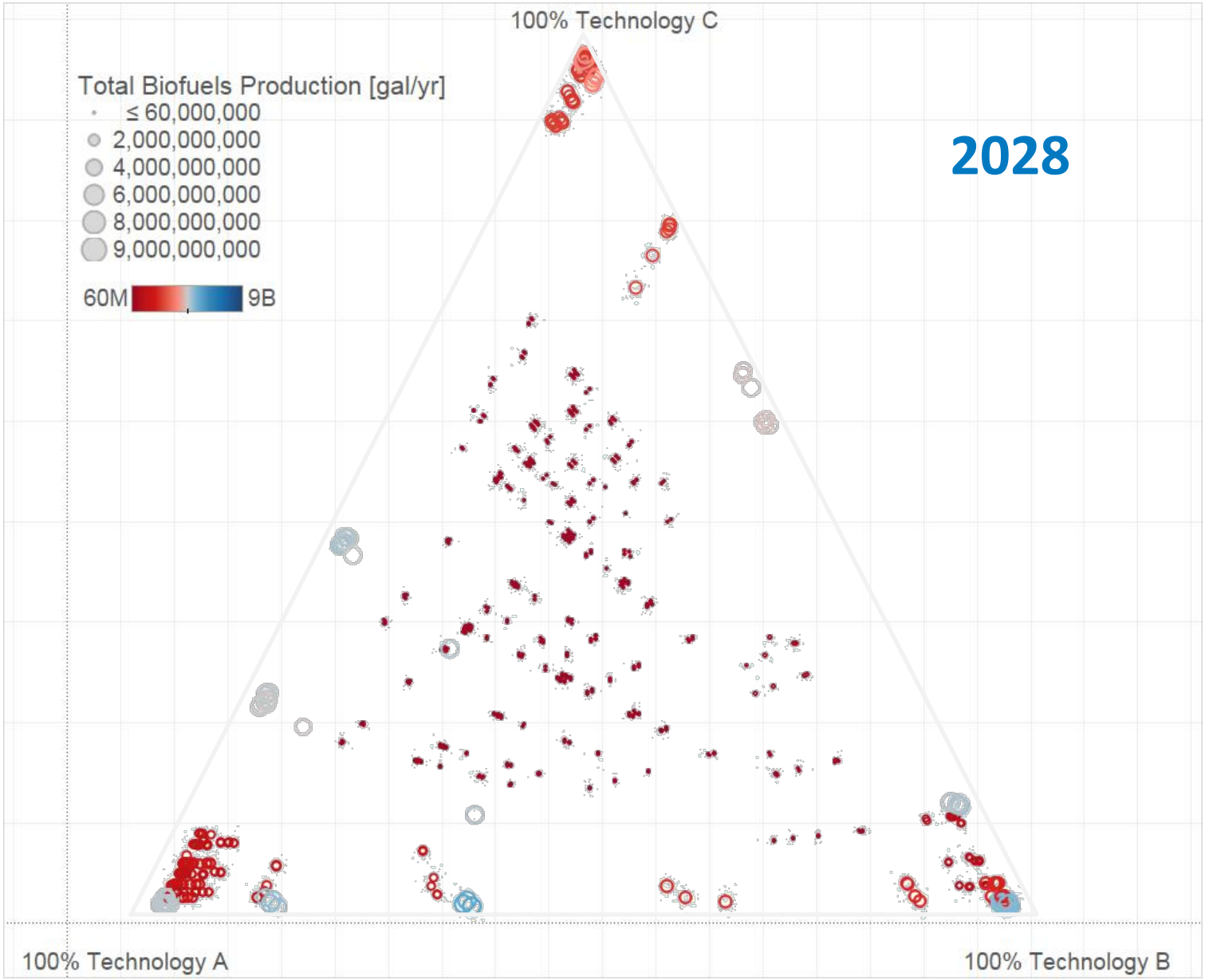

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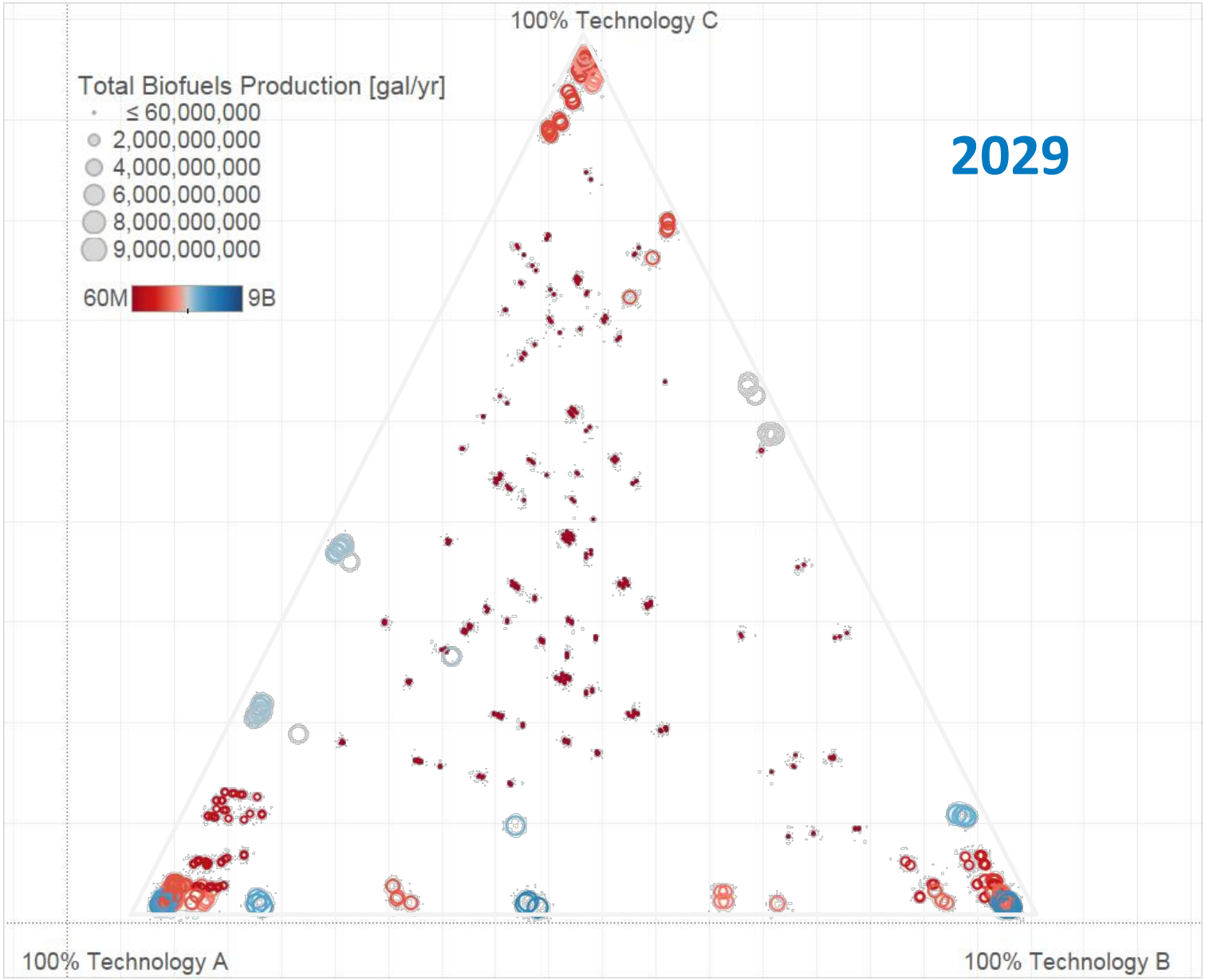

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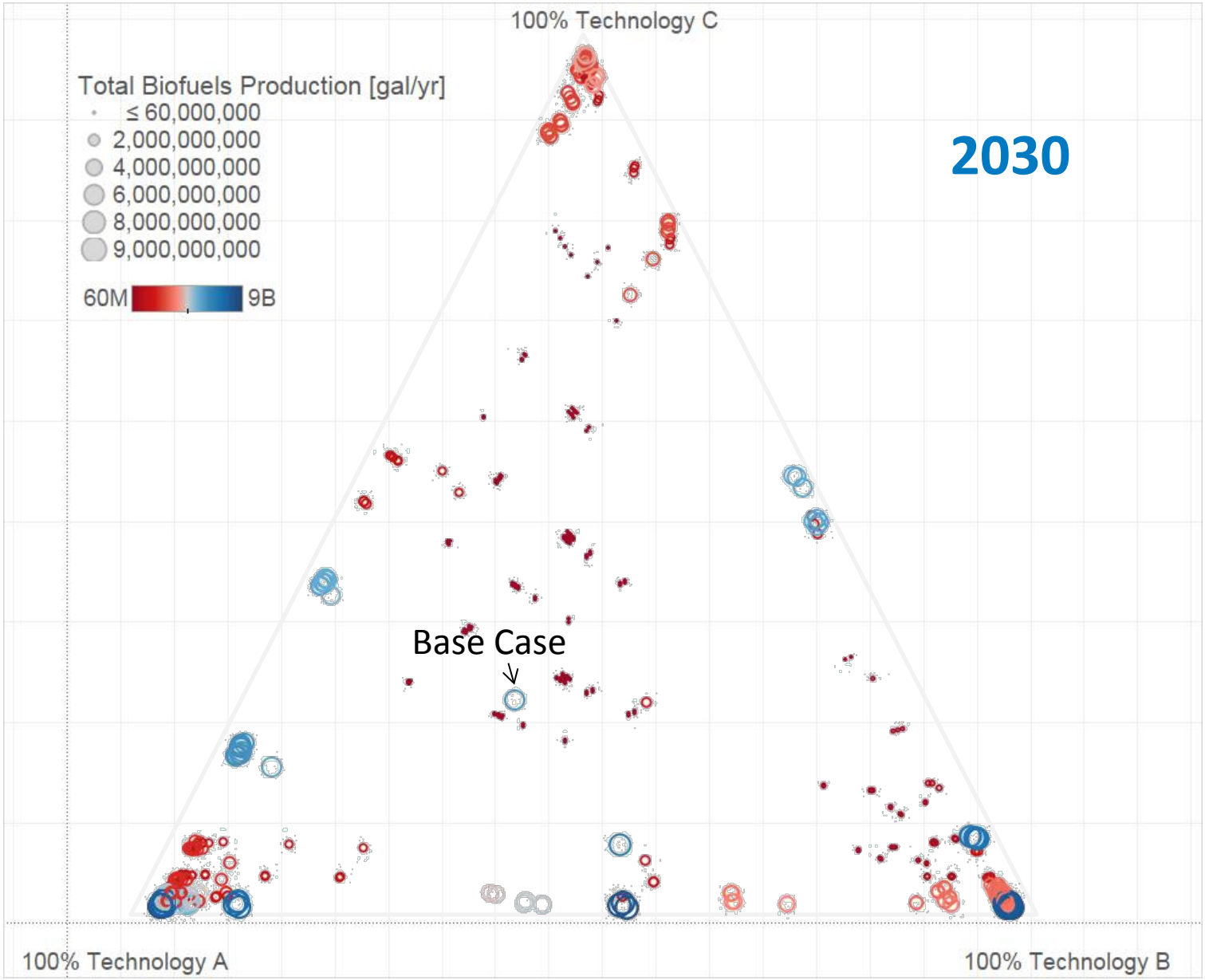
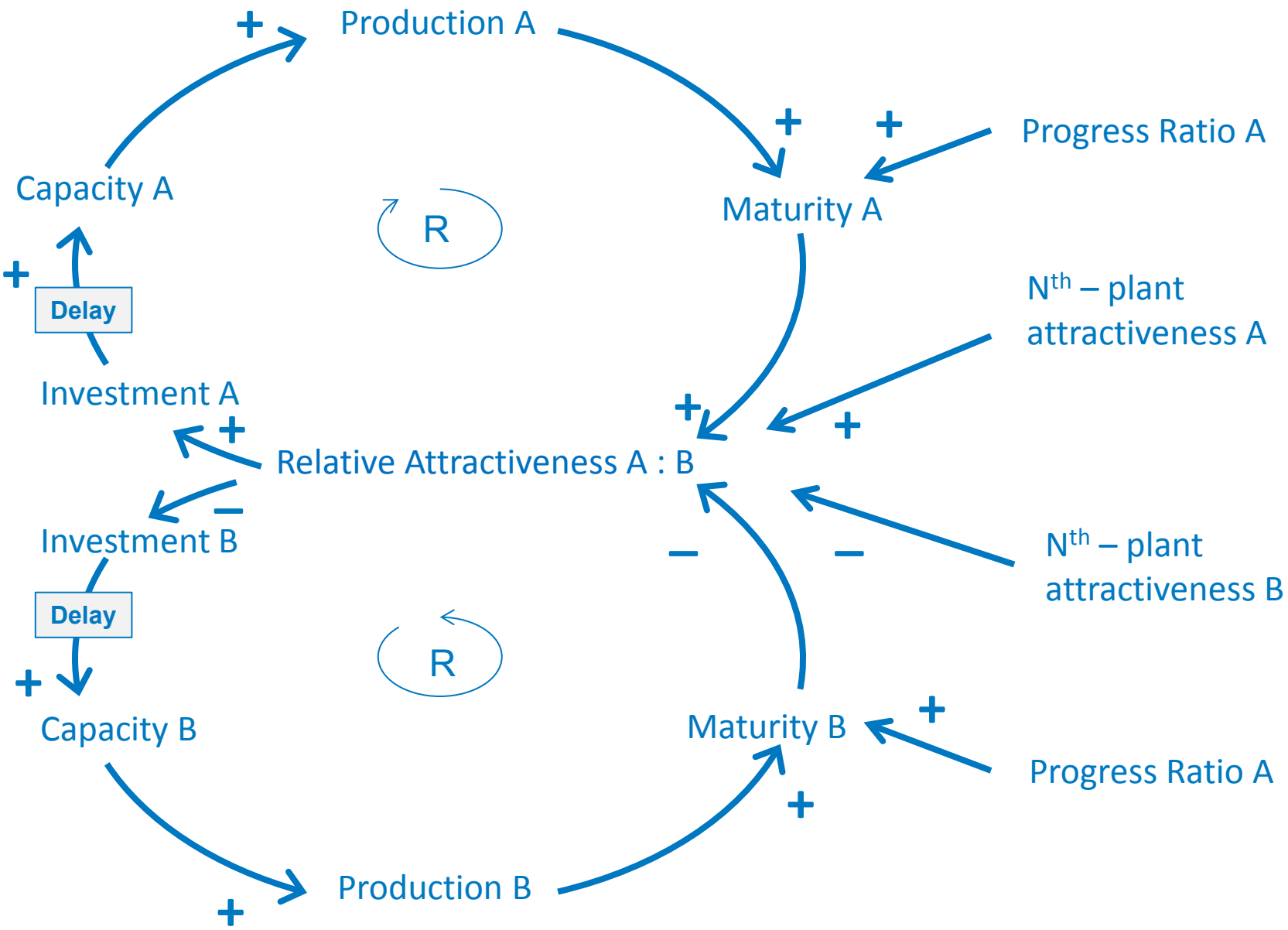


# Mechanism for interactive effects based on learning and competition for investment



# Summary

- Novel Learning Model approach contrasts with single-factor learning
  - Progress toward mature performance instead of an implicit zero asymptote
  - Multiple technical attributes instead of only unit cost
  - Multiple development scales.
- Parameters studied exhibit highly interactive effects
  - Fixed capital investment
  - Process yield
  - Progress ratios
  - Pre-commercial investment
- System shows tendency towards market dominance of a single pathway
- Result are not predictive but illustrative
- Broad applicability to emerging industries to show interactions among:
  - Investment decisions
  - Cost reductions during development
  - Utilization and production