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Essential Elements of Survival and Differentiation in the Upstream Solar Manufacturing in India

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Managing the Dynamic Solar Value Chain is a Requirement for Survival

	2010	2026
Polysilicon Platform	Siemens + FBR	85% Siemens + 15% FBR
Crystal Growth Platform	DSS, CZ, RCZ	RCZ
Slicing Platform	Slurry slicing, DCW	DCW
Cell Platform	AlBSF	TOPCon (Some PERC, HJT)
Module Platform	Full cells, backsheet	Half cells, GoG
Polysilicon Price ($/kg)	$80-$90/kg	$6.5/kg
Wafer Price ($/Wafer)	$4/wafer (156 x 156)	$0.22 [$0.28]/G12 Wafer
Module Price ($/W)	$1.5-$2/W	$0.09 [0.11]/W
CAPEX/GW	$ 1,000 M/GW	$131 M/GW
LCOE ($/kWh)	$0.30-0.40/kWh	$0.03/kWh

Note: Numbers in square parenthesis indicate sustainable prices in a rational market.

- Only those corporations that executed this historical roadmap survive today in China.
- The changes in polysilicon and crystal growth & wafering were driven by the roadmap execution on the same technology platforms. Roadmap execution is the key to survival.

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India Can be Cost Competitive With China at Maturity

Cash Cost ($/W-Module)		
	India at Maturity	Very Long Term
Polysilicon	0.005	0.003
Wafer	0.006	0.004
Cell	0.018	0.016
Module	0.049	0.040
Total	0.078	0.063

Module Cash Cost today: $0.12/W

LCOE 0.03/kWh

Target Module Cost after Maturation $0.078/W

LCOE 0.015/kWh

Module cash cost over a very long term

$0.063/W

LCOE 0.01/kWh

250 GW Manufacturing Capacity in India for domestic and global supply

- Polysilicon by Siemens or FBR
- Crystal Growth by RCZ or CCZ
- Slicing by DCW
- Cells by TOPCon/HJT/xBC
- Requires sector and cultural maturity
- Perovskite-silicon tandems will improve this further.

Note: All numbers are for India under sustainable conditions

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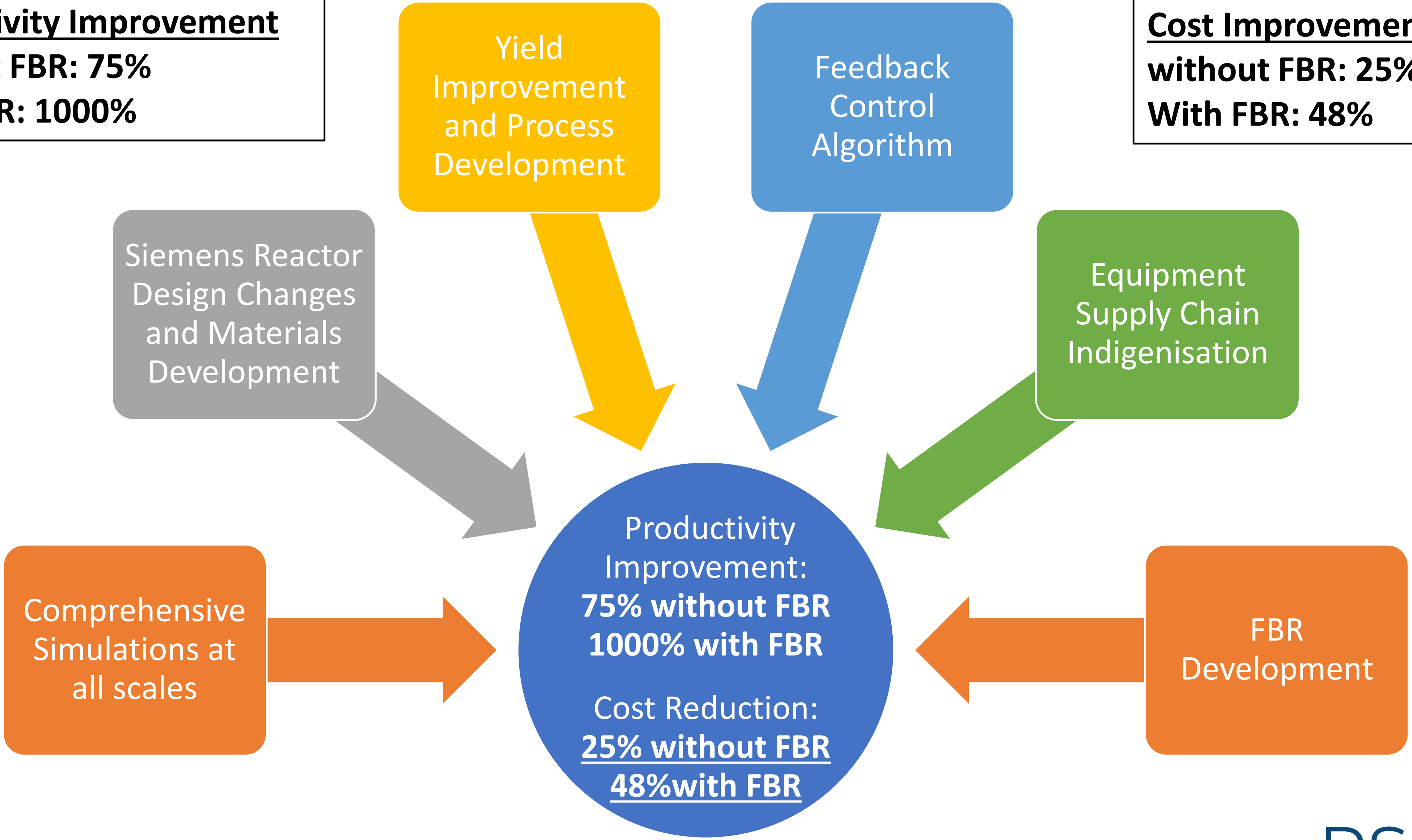
Elements and Impact of Polysilicon Roadmap

<u>Productivity Improvement</u>
Without FBR: 75%
With FBR: 1000%

<u>Cost Improvement</u>
without FBR: 25%
With FBR: 48%



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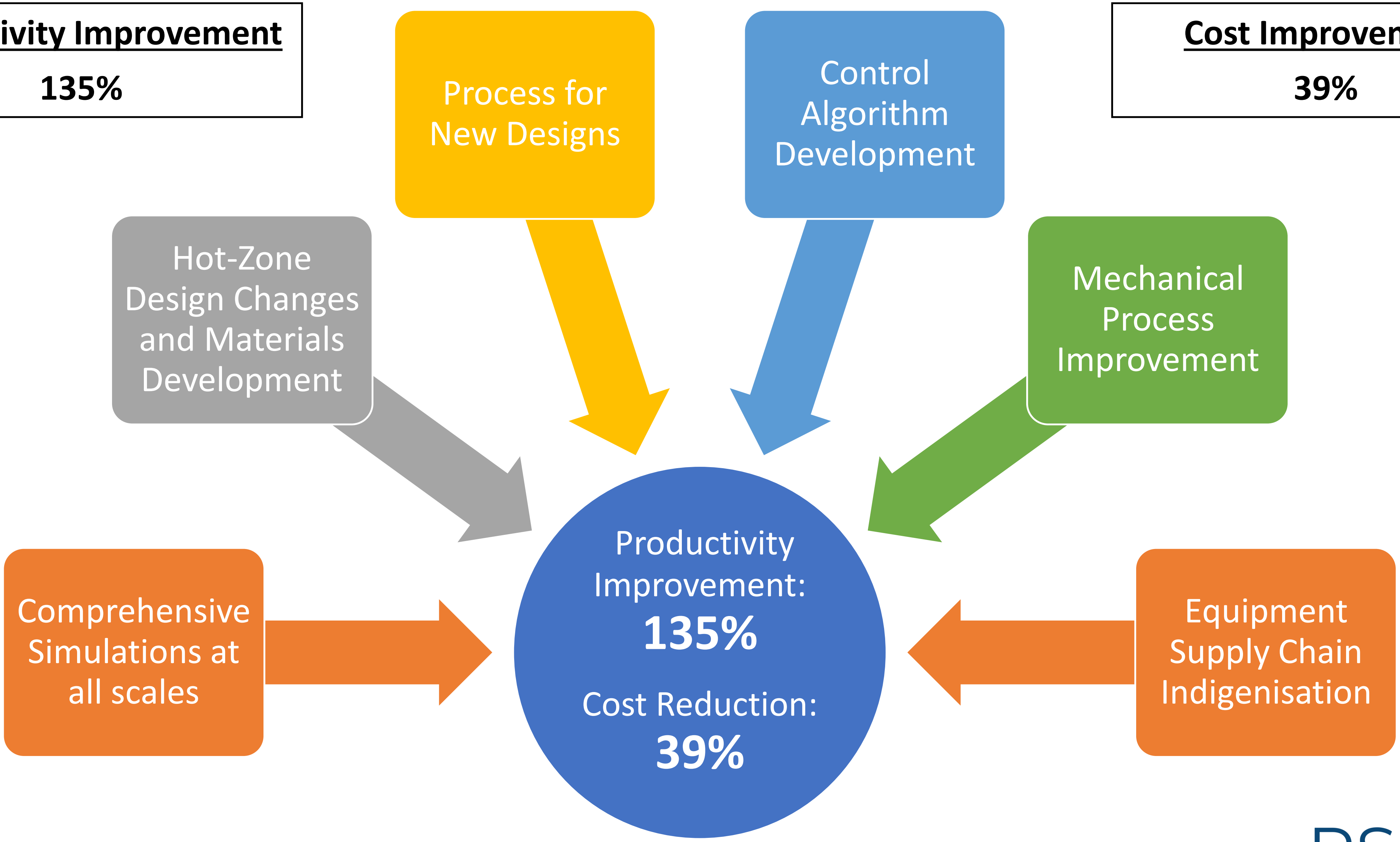
Elements and Impact of Crystal Growth and Wafering Roadmap

<u>Productivity Improvement</u>

135%

<u>Cost Improvement</u>

39%



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A Partial List of Core Competencies Required for Success

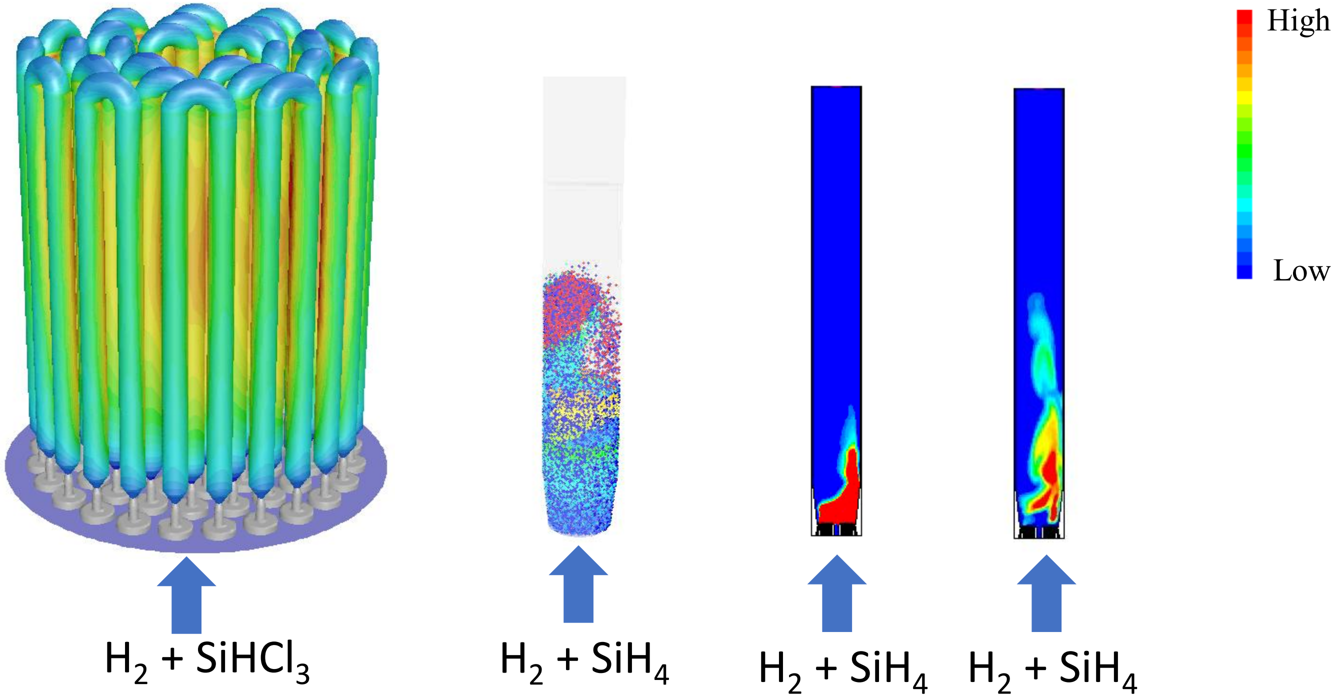
Polysilicon

- Fluidization engineering and reactive systems, multiphase reaction chemistry and engineering
- Distillation, Reactive distillation, Mass Transfer and Reactive mass transfer processes
- Dynamics of Siemens reactors, Multiphase reactions, CVD, Gas phase nucleation, Heat, Momentum and Mass Transfer
- Development of proprietary control platform to differentiate from the competition and continuous improvements in process automation and control
- Continuous innovation to improve the Siemens and FBR reactors and their designs for delivery of the roadmap
- Innovation based on quantification of all operations at various and length and time scales. Quantification based development.
- Manage process, design, and product innovations through well defined pipeline and transfer them from technology to HVM (High Volume Manufacturing)

Crystal Growth and Wafering

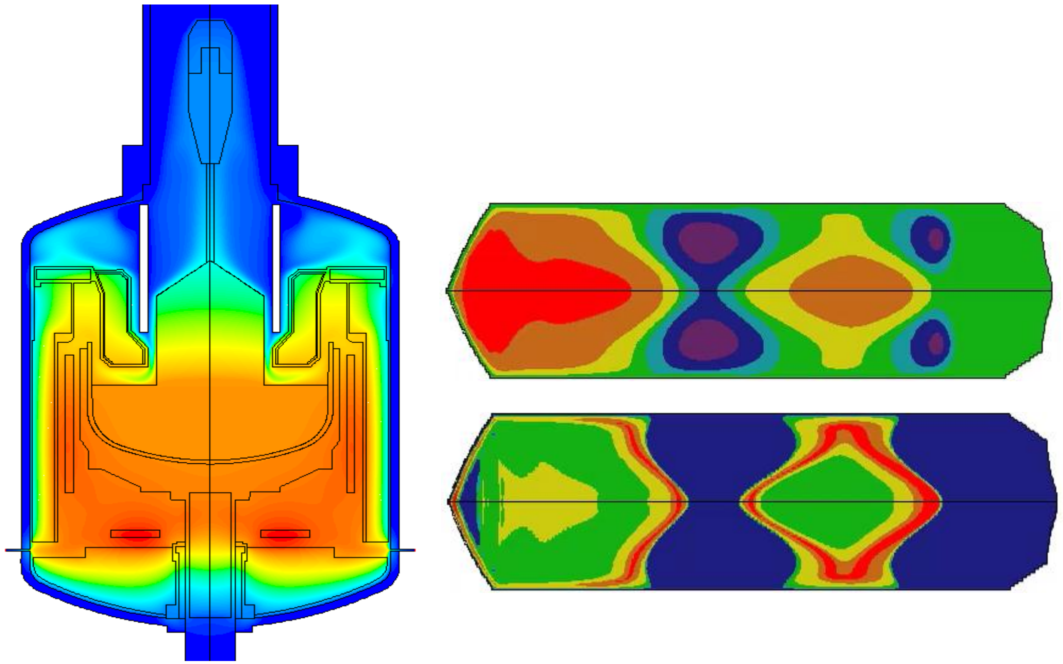
- Development of new Crystal Growth Processes with the existing as well as modified hot-zone and design
- Continuous quality and performance improvement of silicon, graphite, CCM, and quartz materials to improve productivity and quality at low cost
- Development of proprietary control platform to differentiate from the competition and continuous improvements in process automation and control
- Evolutionary improvements to slicing and shaping processes without major equipment modifications
- Continuous innovation to improve the crystal puller hot-zone and design for delivery of the roadmap
- Innovation based on quantification of crystal growth and wafering at various and length and time scales. Quantification based development.
- Manage process, design, and product innovations through well defined pipeline and transfer them from technology to HVM

The Beginning of Roadmap Execution is by Benchmarked Simulations



Left: Complete benchmarked simulation of silicon deposition in a Siemens Reactor.

Right: Fluidised bed reactor dynamics (particle motion, silane conversion, and dust formation, respectively)



Left: A Hot-Zone design and simulation. From**: Voronkov, Dai, and Kulkarni**, SEST, volume 3, pp. 81–169, 2011

Right: Prediction and control of defects in silicon (Future Applications). From: **M. Kulkarni**, J. Cryst. Growth, 303, 2007.

- ❑ A differentiated company must develop unique and proprietary polysilicon reactor and crystal puller hot-zone designs based on accurately benchmarked simulations. Theses simulations are followed by design and fabrication to design. Finally, new designs and processes are implemented in the manufacturing scale technology equipment before introduction into high volume manufacturing.

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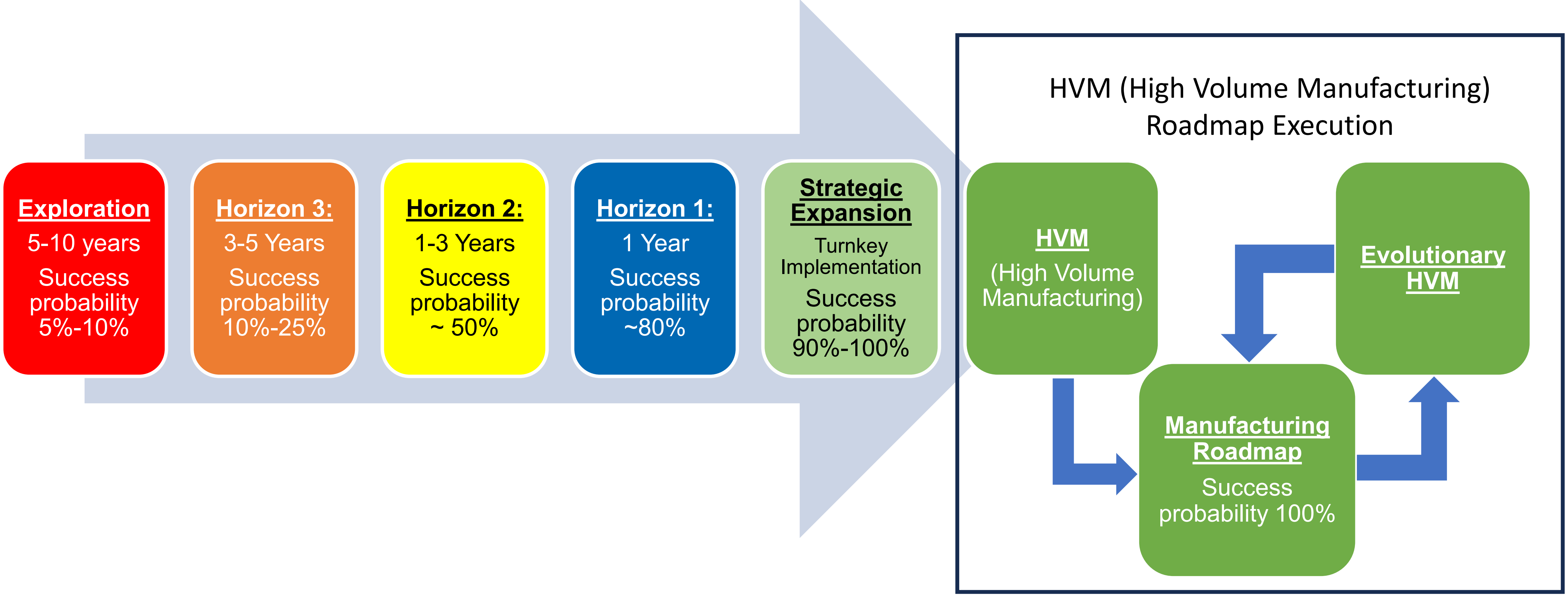
Indigenization of the Relevant Equipment Supply Chain

- The simulation and design capabilities allow development of relevant local supply chain:
  - Polysilicon reactors and vessels can be fabricated in India for any design. Siemens reactor electrical supply system and a few minor supplies must be procured from outside and this can be indigenised in 3 years.
  - Crystal Pullers last for more than 15 years. The crystal puller performance depends on the hot-zone design, which is entirely made of graphite, CCM, quartz, and steel parts. Indian companies and MNCs in India can fabricate these parts to design. This capability can be developed in 3 years.
  - High quality quartz mining and high quality crucible production can also be indigenised.
  - Production of diamond coated wire can be indigenised by licensing the technology.

Culture: India Must Address the Big Gorilla in the Room



- HVM roadmap execution is central to survival and differentiation in solar manufacturing
- Traditional Indian manufacturing sector does not yet have comfort with HVM roadmap execution
- India Inc will take time to develop appreciation for how the solar manufacturing sector works.
- Optimal change management by both driving the change and following the change is needed.
- Vendors cannot provide differentiation by definition. Vendors proliferate what they can develop.
- **Vendor services are necessary but not sufficient. Differentiation has to be earned by a manufacturer.**

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Key Timelines of Interest

- It will take 7-10 years for any Indian company that adopts technology mindset and culture to be competitive with China in polysilicon and crystal growth.
- There will be competition within India in this timeframe. Those companies that adopt technology centric culture will outperform their Indian competition within 3-5 years.
- The best way to accelerate global competitiveness is to hire critical mass of technologists and experienced operations professionals who have more than 15 years of experience in the sector and then build the technology company bottoms-up.
  - This approach can deliver the world class company competitive with Tier1 China companies in 2-3 years.
- Technology is the engine that keeps a solar company moving.

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Summary

- Execution of roadmap on the existing platforms is required for survival and differentiation in polysilicon production and crystal growth & wafering.
  - The present platforms for polysilicon production and Crystal Growth will remain viable in future (proliferation of FBR is difficult because of complexity and IP), but the productivity and cost will significantly improve by the roadmap execution.
  - Those companies that do not execute the roadmap perish, those that execute the bare minimum roadmap required for survival will survive, and those who excel in roadmap execution will differentiate from competition.
- Optimal project execution is a requirement but it is not sufficient. The critical requirement is the roadmap execution after project execution.
- Vendors and consultants have a key role to play but they cannot offer differentiation by definition. Technology driven manufacturing is the business of manufacturers.
- Indian companies need to build organizational core-competencies required for technology and manufacturing roadmap execution.
- Indigenise relevant supply chain in 3 years by developing design capabilities.
- Indian companies need a culture shift from “license and build” philosophy to “technology driven manufacturing” philosophy.

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