TAKSHASHILA INSTITUTION

From Gigawatts to Megawatts

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This report examines the operational principles of SMRs, their distinction from conventional nuclear power plants, economic viability, supply chain vulnerabilities, and India's approach to SMR development.

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1 Abstract

Small Modular Reactors (SMRs) represent a significant technological shift in nuclear power generation, offering scaled-down versions of traditional nuclear reactors—with output capacities generally ranging between 20 and 300 MWe (Megawatt electrical). This paper examines the operational principles of SMRs, their distinction from conventional nuclear power plants, economic viability, and critical components and supply chain vulnerabilities. Furthermore, it outlines India's approach to SMR development, drawing from recent technical literature, economic analyses and policy developments.

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2 Introduction

Global energy systems face unprecedented pressure to decarbonise while maintaining baseload power capacity. While nuclear energy continues to offer a credible pathway towards low-carbon electricity, large-scale reactors face challenges in deployment timelines, capital requirements, and grid infrastructure compatibility. SMRs, meanwhile, have emerged as a potentially transformative technology that could overcome several inherent limitations of conventional nuclear plants.[1]

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SMRs are defined by the International Atomic Energy Agency (IAEA) as advanced nuclear reactors that produce up to 300 MWe of electricity, which is approximately one-third the generating capacity of large nuclear reactors.[2] What distinguishes SMRs from broader nuclear technology is not merely their size, but their design philosophy of modularity, factory fabrication, and standardised serial production.[3] These characteristics alter the cost structure, construction timeline, and deployment flexibility of nuclear power.

India's nuclear sector is positioning itself at the forefront of global SMR initiatives. The announcement of INR 20,000 crore in the Union Budget 2025-26 for SMR design, development, and deployment under the Nuclear Energy Mission for Viksit Bharat signals a significant policy commitment.[4] This is tied to the goal of operationalising at least five indigenous SMRs by the year 2033. This paper examines these developments within the broader context of technological capabilities, economic viability, and geopolitical competition for advanced nuclear technology. It concludes that while SMRs can serve as a stabilising source of energy for India's grid, it will take at least a decade for the technology to mature to that level. India, on the other hand, needs energy resilience far more urgently.

3 Why SMRs?

Before unpacking the developments around SMRs, it is crucial to first understand why this technology is becoming increasingly important in energy discourse. As emerging technologies—such as Artificial Intelligence (AI), large-scale machine learning and cloud services—proliferate, they are driving a rapid expansion of energy-intensive compute infrastructure and data centres. This creates a structural increase in electricity demand, particularly for highly reliable, round-the-clock power that can sustain digital infrastructure and critical services without interruption.

At the same time, states are closing in on the 2050 target for achieving net-zero carbon dioxide emissions under the Paris Agreement, thereby intensifying pressure to decarbonise power systems at scale and speed. Institutions such as the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) have repeatedly underlined that most credible net-zero pathways require a substantial increase in nuclear-generated electricity, alongside renewables and demand-side efficiency.[5] In other words, nuclear energy is no longer framed as an optional technology, but as a core pillar of decarbonisation strategies in many scenarios.

Moreover, in the context of India's grid, SMRs are uniquely relevant as a stabilising source of energy. Solar power generation surges during the day but dips sharply in the evening just as demand peaks. The rapid adoption of air conditioning and heavy industrial growth has created a hard-to-manage surge in evening demand that coal thermal plants cannot flexibly meet, as it takes hours to increase or reduce their generation.[6]

Gas-fired plants currently help bridge this gap to a limited extent, as they can ramp up and down more quickly than coal. However, India's domestic gas production is insufficient, and the country depends significantly on imported Liquefied Natural Gas (LNG).[7] This dependency has been strained by the ongoing conflict in West Asia, which has disrupted LNG tanker routes, driving up spot prices and creating supply uncertainty at precisely the moments of peak grid stress.[8]

In addition to requiring battery storage or gas-fired plants to meet demand, the renewable energy sector faces significant delivery risks. Approximately 38.3 GW of capacity was cancelled between 2020 and 2024 due to tender design issues and undersubscription, as well as Power Sale Agreement (PSA) delays.[9] Furthermore, numerous renewable energy projects get frequently delayed as a result of unfinished transmission lines[10] and regulatory complexities—such as around land acquisition.[11]

SMRs offer a partial but meaningful alternative. Like gas, SMRs can modulate output more responsively, but are insulated from fuel price volatility and geopolitical supply disruption owing to longer refueling cycles and domestic uranium enrichment capabilities. A fleet of SMRs sited near industrial demand centres or retiring coal plants could provide dispatchable power during evening peaks, without the intermittency that makes solar power insufficient on its own as a grid stabiliser.

Within this context, SMRs also emerge as a promising response to several longstanding political and economic barriers associated with conventional gigawatt-scale nuclear power plants. Such reactors typically involve very high upfront capital expenditure, large and complex construction sites, and long lead times—all of which create significant financing and project-risk challenges. SMRs, by contrast, are designed to be factory-fabricated, modular and smaller in unit size. This, in principle, can help lower capital commitments per project, enable more incremental capacity additions, and reduce construction-related delays and cost overruns.

Safety perceptions and regulatory confidence are also central to the debate. SMR designs incorporate passive safety features and underground[12] or underwater[13] siting options that aim to reduce the probability and potential impact of severe accidents. This is politically salient in countries where public acceptance of nuclear energy remains fragile.

Underground siting involves placing the reactor module and its critical safety systems below ground level, typically in rock caverns.[14] SMRs can also be deployed in the seas—either as floating reactors or placed on the seabed.

At the same time, SMRs preserve the key advantages of nuclear power when compared with variable renewables such as solar and wind power. While renewables remain essential for decarbonisation, their output depends on weather conditions and typically requires complementary storage or flexible backup generation to ensure a continuous supply.

SMRs—by providing low-carbon, dispatchable and uninterrupted power—can therefore complement renewables, support grid stability, and serve as a reliable backbone for both industrial loads and emerging digital infrastructure. Indigenous SMR development, if successful, also provides technology export potential to low and middle-income countries while reducing energy import dependencies through fuel diversification partnerships.

4 How SMRs Work

4.1 Fundamental Physics and Engineering

The basic operating principle of SMRs mirrors conventional nuclear power plants, employing controlled nuclear fission within a reactor core. The mechanism consists of three primary phases: heat generation, steam generation, and electricity production.

Feature	SMRs	Conventional Large Reactors
Power Output	Typically up to 300 MWe per unit.	Typically 700 MWe to 1,000+ MWe.

Feature	SMRs	Conventional Large Reactors
Physical Size	Rolls-Royce's proposed 470 MWe SMR requires roughly 0.04 square km, but the size varies based on factors such as reactor design and generating capacity.[15] Exclusion zones typically range from 0.4 km for a 50 MWe reactor, to 0.8 km for a 300 MWe reactor.[16]	Occupies ~2 square km, with an exclusion zone radius of at least 1.5 km.[17]
Construction	Factory-built modules; transported and assembled on-site.	Primarily on-site (bespoke) construction over several years.
Safety Systems	Relies on passive safety (gravity, natural convection) with minimum human intervention.[18]	New reactor designs generally have a mix of passive and active safety systems.[19]
Refuelling Cycle	Depends on the design. Most water-cooled SMRs have a 1 to 2 year cycle. Some designs target up to 25 years without refueling.[20]	Typically every 1 to 2 years. However, Indian Indian Pressurised Heavy-Water Reactors (PHWRs) are refueled while in operation (typically on a daily basis).[21]
Capital Investment	High initial capital cost per unit which may decline depending on fleet expansion and maturing of supply ecosystem.	High capital cost.
Deployment Time	Projected to be between 3 to 3.5 years.[22]	Typically 5 to 10 years.

Feature	SMRs	Conventional Large Reactors
Siting Flexibility	Can be deployed in remote areas, near industrial sites, underground[23] or underwater.[24] Exclusion zones depend on factors such as design and generation capacity.[25]	Less flexible, and exclusion zones depend on factors such as design and generation capacity.

Table 1: Difference between SMRs and conventional nuclear reactors.[26]

4.1.1 Heat Generation

Nuclear fission reactions within the reactor core generate intense heat. Nuclear fuel, typically uranium-235 or other fissile materials, undergoes controlled chain reactions. Control rods—composed of neutron-absorbing materials such as boron or cadmium—regulate neutron populations by absorbing excess neutrons, thereby preventing uncontrolled reactions and maintaining sustained and manageable heat output.

4.1.2 Steam Generation

The heat from the reactor core converts water into high-pressure steam, which drives turbines to produce electricity.

In most SMRs—such as pressurised water designs by NuScale Power—the primary coolant circulates in a closed loop within the reactor vessel, transferring heat to a secondary loop that generates steam. This isolates radioactive primary fluid from the clean secondary loop.[27]

Advanced designs vary; high temperature gas cooled SMRs, liquid metal cooled fast neutron spectrum reactors and molten salt reactors generally use helium, sodium and fuel salt as coolants.[28]

4.1.3 Turbine Dynamics

This steam drives a turbine connected to an electrical generator, converting thermal energy into rotational kinetic energy and subsequently into electrical power.[29]

Figure 1: Electricity generation in an SMR.[30]

This flowchart was generated using Napkin AI.

4.2 Safety Mechanisms

Statistically, nuclear energy is one of the safest forms of power generation. Mortality rates are calculated in deaths per terawatt-hour (TWh), which includes deaths from accidents (mining, construction, operation) and long-term health effects (air pollution). Death rates per unit of electricity production via nuclear energy is one of the lowest (0.03) when compared to other forms of electricity production.[31]

Official estimates of Chernobyl[32] and Fukushima casualties are considered undercounts by some researchers, who argue that long-term cancer deaths from low-level radiation exposure are systematically underreported.[33] However, even under more aggressive casualty estimates, nuclear energy compares favorably to fossil fuels per TWh.[34]

SMR safety is essentially built on three principles: small core advantages, passive cooling systems, and simplified integral designs that reduce the number and severity of potential failure points.

As a result of smaller cores, SMRs generally have lower power density and reduced fuel inventory, which reduce the risks of major accidental consequences.[35] Some SMR designs include passive safety systems that use natural processes, such as natural circulation and convection for the removal of decay heat; making it possible to cool the core without external power sources.[36]

In addition to technical safety features, proliferation is another aspect that is key to identifying potential risks vis-à-vis nuclear energy sources. Proliferation risks of SMRs are debatable. For instance, on one hand, some SMR designs require infrequent refueling ,thus lowering the risks of material diversion. On the other hand, some designs require highly enriched uranium or have more integrated designs that are harder to inspect, which increases proliferation risks. The degree of such risk would, therefore, depend upon technical aspects, local governance, and regulatory requirements.[37]

5 Geopolitical Significance

5.1 Uranium Production and Geographic Concentration

Global uranium mining remains geographically concentrated, with around three-quarters of output coming from a small set of countries led by Kazakhstan (about 40% of world production in 2024), Canada, Namibia, and Australia. India, the US, Russia, Uzbekistan, Niger, China and others contribute smaller volumes, leaving most consuming states dependent on imports from this narrow producer group.[38]

SMR fuel types include:

- Slightly Enriched Uranium (SEU) (0.9–2% U-235) for heavy-water reactors such as PHWR variants.
- Low-Enriched Uranium (LEU) (typically between 3-5% U-235 but less than 20%) for light-water designs like pressurised water reactors.

- High-Assay Low-Enriched Uranium (HALEU) (5–20% U-235) for advanced SMRs.[39]

Uranium enrichment levels determine fuel suitability for different reactor types, with natural uranium—at approximately 0.7% U-235—requiring processing to increase the fissile isotope concentration in order to sustain a chain reaction.[40] Geographic concentration combined with limited processing and enrichment alternatives, especially for HALEU, creates strategic dependencies with potential for supply disruptions.[41]

Geopolitical considerations and bottlenecks vary by type. LEU faces concentrated mining and enrichment (Russia, EU, US, China), and is sensitive to sanctions and price volatility. SEU requires minimal enrichment (0.9–2% U-235). Security requirements for both SEU and LEU may slightly differ from HALEU. This is owing to potentially enhanced proliferation concerns associated with uranium that is comparatively more enriched.[42]

HALEU encounters the highest risks due to fewer commercial producers, stricter safeguards, and leverage for supplier states over SMR deployment, as many designs anticipate it. All share vulnerabilities arising from Kazakhstan's dominance and Western-Russia/China market bifurcation.[43]

India's Bharat Small Modular Reactor (BSMR-200) is a pressurised water reactor designed around SEU fuel. Since SEU avoids HALEU's acute bottlenecks and scrutiny, India faces primarily generic risks like uranium price swings. Domestic mining expansion, import contracts, and limited enrichment under safeguards should insulate BSMRs from severe global SMR fuel constraints, though the politicised uranium market persists.

5.2 Specialised Materials and Component Supply Chains

Beyond fuel, SMRs require specialised materials such as advanced zirconium alloys, nuclear-grade pressure vessel steels, and Nickel-Cromium-Molybdenum alloys that only a limited number of certified mills and forges worldwide can produce.[44] India has domestic reserves and processing foundations for zirconium and rare earth elements, and is actively investing in rare earth magnet manufacturing.[45] While India is self-sufficient in nuclear-grade zirconium for its heavy-water reactors,[46] current production capacity for rare earth elements is limited.[47]

When it comes to manufacturing components required in SMRs, India already possesses the heavy forging capabilities, the turbine assembly lines, and the nuclear-grade electronics sector—with organisations like L&T[48] and BHEL[49] leading in this space.

6 Economic Viability of SMRs

Large nuclear reactors in the US have increasingly led to cost overruns as a result of the rise in the cost of containment buildings. This is owing to low labour productivity.[50] Given the smaller size and modularity of SMRs, it is assumed to be more economical. However, SMRs inherently lack the benefits of economies of scale that favour larger reactors.

Moreover, large reactors have historically had negative learning rates but have the benefits of economies of scale, as they distribute fixed costs over a much larger electrical output. To overcome the inability to scale, SMRs need to be mass-produced and with high learning rates. Currently, they are projected to achieve 5-10 per cent learning rates.[51]

Learning rate is the percentage of reduction in costs achieved with each doubling of cumulative installed capacity, or production.

Scaling coefficient (k) quantifies economies of scale and denotes the reduction in cost per unit of power as the plant size increases. To illustrate this, building a nuclear power plant that is twice as big as another would not cost twice as much, but instead would cost 2k times as much. Given the rule-of-thumb coefficient is 0.6, a nuclear plant double the size would cost 20.6 times the original cost, which is about 1.5 times. In other words, increasing the capacity by 100 per cent would increase the cost by 50 per cent.

To put this in numbers, for k=0.6, the following number of 300 MWe SMRs need to be deployed—depending on the learning rate.

Learning Rate	Number of 300 MWe SMRs
5 per cent	671
10 per cent	24
15 per cent	8

Table 2: Number of units needed to compensate for the lack of economies of scale in SMRs (300 MWe), as projected by Nøland, Hjelmeland, and Korpås.[52]

The Levelised Cost of Electricity (LCOE), which is the cost per unit of energy to build and operate a power-generating asset over its entire lifetime, is another financial metric used to determine the feasibility of such plants.

In the Indian context, the LCOE for SMRs is heavily dependent on the maturity of the technology. Current estimates for First-of-a-Kind (FOAK) units are significantly higher than the domestic coal or large-scale nuclear alternatives. However, with mass production and maturity, costs may go down.[53]

The financing cost component of the LCOE is reduced by the shorter construction timelines of SMRs, estimated at 3 to 5 years.[54] This reduces the interest incurred during construction, which can otherwise account for up to 30 per cent of total project costs in traditional nuclear builds.[55] Moreover, the coal-to-nuclear strategy, where countries plan to repurpose retired thermal plants and utilise existing grid connectivity, land, and auxiliary buildings can significantly lower the initial capital burden for India's SMR programme.[56]

Even if SMRs have a higher LCOE than solar or wind power, their economic value will be found in the capacity factor. The aim for land-based, water-cooled SMRs is to have a capacity factor of over 90 per cent,[57] whereas solar plants globally operate at 17 per cent (as of 2024).[58]

7 India's SMR Development Programme and International Partnerships

7.1 Indigenous Development Programme

India's SMR initiative centers on the Bharat Small Modular Reactor (BSMR) programme, a nationally important project advancing India's indigenous nuclear technology capabilities. In August 2025, the Nuclear Power Corporation of India Limited (NPCIL) and Engineers India Limited (EIL) formalised collaboration through a Memorandum of Understanding targeting conceptual design and development of the BSMR.[59]

India is also developing SMR-55 and High-Temperature Gas-Cooled Reactors (HTGCR) which are not covered in this paper. The former is a 55 MWe SMR, while the latter is a 5 MWth (Megawatt thermal) SMR meant for hydrogen generation.

The 220 MWe Bharat Small Reactors are not modular but smaller versions of existing PHWRs.[60]

Feature	Small Modular Reactor (SMR)	Bharat Small Reactor (BSR)	Bharat Small Modular Reactor (BSMR)
Origin/Scope	Global classification for any modular reactor ≤300 MWe.	Indigenous nuclear reactor based on existing PHWR technology.	New indigenous SMR technology currently in the R&D phase.
Technology	Various: Pressurised Water Reactor (PWR), Gas-cooled, Fast-neutron, etc.	PHWR	PWR (Light Water)
Capacity	Typically 20 MWe to 300 MWe per module.	220 MWe	200 MWe

Feature	Small Modular Reactor (SMR)	Bharat Small Reactor (BSR)	Bharat Small Modular Reactor (BSMR)
Fuel Type	Various but mostly HALEU.[61]	Natural Uranium	SEU
Status (as of 31 March 2026)	Various (some operational in Russia/China).[62]	Request for proposals to finance a fleet of BSRs extended to 31 March 2026.[63]	In-principle approval received. Construction will take five to six years from receipt of administrative and financial approval.[64]

Table 3: Difference between SMRs, BSRs, and BSMRs.[65]

NPCIL has issued a call for proposals inviting Indian industries to participate in setting up 220 MWe Bharat Small Reactors for captive power generation, targeting industrial decarbonisation. The government has committed to a partnership with private players for BSMR deployment, representing a strategic shift toward private sector participation in India's nuclear sector.[66]

The BSMR program aligns with India's broader Nuclear Energy Mission for Viksit Bharat, which targets a nuclear power capacity of 100 GW by 2047. Currently, India operates 24 operational reactors generating approximately 8.7 GW of capacity,[67] and achieving 100 GW by 2047 requires approximately 74 GW of additional capacity. This target demands substantial technological innovation and infrastructure investment.

The legislative landscape for nuclear energy in India underwent a structural transformation with the enactment of the Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India (SHANTI) Act of 2025. This landmark legislation replaced the restrictive 1962 Atomic Energy Act, thereby shifting the sector from a state-controlled monopoly to a regulated, multi-player market.

For nuclear reactors, the act serves as a catalyst for commercialisation by streamlining the licensing process through a dual-permit system, consequentially separating central government licenses from safety authorisations.[68] Beyond administrative restructuring, the SHANTI Act may improve the ease of doing business. Under the new regime, private conglomerates are permitted to build, own, and operate nuclear facilities—with provisions for Foreign Direct Investment (FDI) up to 49 per cent through joint ventures.[69]

7.2 Key Milestones in Bilateral Partnerships

This subsection maps pivotal shifts in India's key nuclear energy partnerships with the US, Russia, Canada and France, leading up to the current focus on SMRs.

7.2.1 1998: The Pokhran-II Tests

On May 11 and May 13, 1998, India conducted a series of five underground nuclear bomb explosions at the Indian Army's Pokhran Test Range in the Rajasthan desert. Immediately following the successful tests on May 11, the then Prime Minister Atal Bihari Vajpayee held a press conference declaring India a full-fledged nuclear weapons state—challenging the global non-proliferation consensus.[70] As a result of the international backlash that followed, India was temporarily isolated from global financial institutions and high-tech trade. To assuage global fears, India quickly articulated a responsible nuclear doctrine, most notably committing to a strict "No First Use" (NFU) policy and maintaining a credible minimum deterrence.[71]

- **US**: Strongly condemned the nuclear weapons tests, immediately imposed strict economic sanctions, and isolated New Delhi on the global stage.[72]
- **Canada**: Recalled its envoy, suspended bilateral trade talks, and halted all nuclear and military exports, hence creating a diplomatic freeze.[73]
- **France**: Broke from the Western consensus by refusing to impose sanctions. Recognising India's strategic autonomy, France became the first Western nation to establish a formal Strategic Partnership with India earlier that same year.[74]
- **Russia**: Maintained its support for India. Moscow refused to join the embargoes, thus ensuring India still had a reliable supplier for military and nuclear technology during its isolation.[75]

7.3 2008: The Nuclear Suppliers Group (NSG) Waiver

On September 6, 2008, the 45-nation NSG granted India an unprecedented, country-specific exemption. Owing to its non-NPT (countries that have never signed or ratified the Treaty on the Non-Proliferation of Nuclear Weapons) status and subsequent weapons programme, India was effectively locked out of the international nuclear market for decades. The country needed this waiver to access the imported uranium fuel and advanced technology required to meet its surging domestic energy demands. Following a diplomatic campaign led by the Bush administration in the US and strict non-proliferation commitments by India, the waiver was granted.[76]

- **US**: Signed the US-India Civil Nuclear Agreement (the 123 Agreement), ending decades of isolation and creating the legal framework for US companies to supply civilian nuclear technology.[77]
- **Canada**: Moved to establish FTA's with India in the aftermath of the waiver.[78]
- **France**: Became the first country in the world to sign a bilateral civil nuclear cooperation agreement with India in September 2008.[79]
- **Russia**: Signed a landmark Intergovernmental Agreement in December 2008, accelerating the expansion of the Kudankulam Nuclear Power Plant with advanced VVER-1000 reactors.[80]

7.4 2010: The Liability Bottleneck

India passed the Civil Liability for Nuclear Damage Act (CLNDA) in 2010. By exposing foreign suppliers to potentially unlimited risk, this law was cited by critics as a factor that stalled the American and French mega-projects (like the planned Jaitapur plant).[81]

- **US**: Developments resulting from the 123 Agreement were stalled as a result of CLNDA.
- **Canada**: Thawed its 1998 freeze by signing a Nuclear Cooperation Agreement in 2010 (fully implemented by 2013).[82] This regulatory milestone led to a major 2015 commercial contract with Canadian supplier Cameco to fuel India's civilian reactor fleet.[83]
- **France**: Progress on the Jaitapur plant stalled for over a decade due to CLNDA.[84]
- **Russia**: Bypassed the CLNDA hurdles partially because the Indian government granted specific liability exemptions to Russian suppliers.[85]

7.5 Collaborations on SMRs

- **US**: Amended the US Atomic Energy Act in 2024, empowering the Nuclear Regulatory Commission to issue commercial licenses to Indian entities.[86] Following this, the US Department of Energy authorised Holtec International to transfer unclassified SMR-300 technology to Indian private firms (like L&T and TCS) for local manufacturing and deployment.[87]
- **Canada**: In March 2026, Canada and India signed a massive CAD 2.6 billion, nine-year uranium supply deal with Cameco.[88] The two nations also formally agreed to cooperate on the development and deployment of SMRs to help India reach its 100 GW nuclear capacity target by 2047.
- **France**: During a February 2026 state visit, India and France signed a formal Declaration of Intent to co-design,

co-develop, and co-produce SMRs and Advanced Modular Reactors (AMRs).[89]

- **Russia**: During the late 2025 annual summit, leadership from both nations pivoted their focus—agreeing to accelerate technical discussions on deploying Russian-designed SMRs, and floating nuclear power plants in India.[90]

8 Conclusion

SMRs represent a meaningful, though not revolutionary, addition to global nuclear technology portfolios. Their operating principles mirror conventional reactors at a smaller scale, but with modular deployment. Economic viability remains contingent on achieving economies of mass production to compensate for the loss of traditional economies of scale. In other words, India must deploy a significant fleet of units to achieve cost-competitiveness with alternatives.

In the immediate term, India's energy resilience is strained by more urgent pressures. By combining the SMR programme with targeted international partnerships, India is building a diversified SMR ecosystem that balances technology access, supply-chain resilience, and regulatory alignment. Consequently, while SMRs will likely serve as a vital grid stabiliser and a tool for industrial decarbonisation, this impact will realistically manifest over a ten-year horizon as the first indigenous designs move from R&D to commercial maturity.

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