

**Evaluating the Impact of National Supercomputing Mission (NSM) in  
India: Challenges, Gaps, and Recommendations for Enhanced  
Effectiveness**

Dissertation Submitted to the Panjab University, Chandigarh for the award  
of degree of **Master of Arts in Public Administration and Public Policy**,  
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Submitted by  
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**50<sup>th</sup> ADVANCED PROFESSIONAL PROGRAMME IN PUBLIC  
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NEW DELHI**

**CERTIFICATE**

I have the pleasure to certify that *Capt Pradeep Pathak, Indian Navy*, has pursued his research work and prepared the present dissertation titled '*Evaluating the Impact of National Supercomputing Mission (NSM) in India: Challenges, Gaps, and Recommendations for Enhanced Effectiveness*', under my guidance and supervision. The same is the result of research done by him and to the best of my knowledge; no part of the same has been part of any monograph, dissertation or book earlier. This is being submitted to the Panjab University, Chandigarh, for the purpose of **Master of Arts in Public Administration and Public Policy** in partial fulfilment of the requirement for the Advanced Professional Programme in Public Administration (APPPA) of Indian Institute of Public Administration (IIPA), New Delhi.

I recommend that the dissertation of *Capt Pradeep Pathak, Indian Navy*, is worthy of consideration for the award of Master of Arts degree from the Panjab University, Chandigarh.

Date : March 25

Place : New Delhi

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Mar 25  
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**DECLARATION**

I, the undersigned, hereby declare that this dissertation entitled '*Evaluating the Impact of National Supercomputing Mission (NSM) in India: Challenges, Gaps, and Recommendations for Enhanced Effectiveness*' is my own work, and that all the sources I have accessed or quoted have been indicated or acknowledged by means of completed references/ bibliography. The dissertation has not been submitted for any other degree of this university or elsewhere.

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**ABBREVIATIONS**

AI & ML	Artificial Intelligence and Machine Learning
AMD	Advance Micro Devices
ARM	Advance RISC Machine
AUM	Advanced Co-DAC (co-design and co-development)
AWS	Amazon Web Series
CDAC	Centre for Development of Advanced Computing
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
CXL	Compute Express Link
DST	Department of Science and Technology
GCC	Global Capability Centres
GPU	Graphics Processing Unit
HPC	High Performance Computing
HRD	Human Resource Development
IISc	Indian Institute of Science
IIT	Indian Institute of Technology
LLNL	Lawrence Livermore National Network
MeitY	Ministry of Electronics and Information Technology
MSME	Micro Small and Medium Enterprises
NCSA	National Centre for Supercomputing Applications
NERSC	National Energy Research Scientific Computing
NSM	National Supercomputing Mission

ORNL	Oak Ridge National Network
PPP	Public Private Partnership
RISC	Reduced Instruction Set Computer
TACC	Texas Advance Computing Centre
TCS	Tata Consultancy Services
TSMC	Taiwan Semiconductor Manufacturing Company

## **EXECUTIVE SUMMARY**

1. The National Supercomputing Mission (NSM) has been a significant initiative aimed at strengthening India's high-performance computing (HPC) infrastructure, fostering research, and reducing dependency on foreign technology. Since its launch, NSM has overseen the deployment of multiple supercomputers across research institutions and universities, thereby enhancing computational capabilities across the country. The mission has also promoted indigenous advancements such as AUM-HPC processors, Rudra server architecture, and Shakti microprocessors, marking a step toward self-reliance in supercomputing technologies. While these developments have improved India's research ecosystem and strategic capabilities, there is still a need for further enhancements to ensure complete technological self-sufficiency.

2. Despite these advancements, optimal utilisation of computational resources remains a challenge, with issues such as inefficient job scheduling, limited accessibility, and a shortage of skilled professionals impacting overall efficiency. Several institutions struggle to maximise the computational power available, highlighting the necessity for capacity-building initiatives, better workforce training, and improved integration of supercomputing infrastructure into academic and industrial applications. Additionally, NSM has been instrumental in driving progress in key areas such as climate modelling, genomics, artificial intelligence, and national security. However, gaps persist in stakeholder coordination, policy implementation, and industry engagement, underscoring the need for improved governance mechanisms and strategic investments to propel the mission forward.

3. The key challenges identified in this study include low infrastructure utilisation, an ongoing reliance on imported components, and a lack of highly skilled professionals in the field of supercomputing. The study also emphasises the need for a centralised governing body that can effectively coordinate efforts between the government, academia, and industry to ensure the optimal use of resources. To overcome these challenges, this dissertation proposes implementing AI-driven workload management, expanding cloud-HPC integration, and fostering public-private partnerships (PPPs) to improve the efficiency of India's HPC ecosystem. Additionally, increased investment in domestic semiconductor manufacturing, research-driven HPC training programs, and a more structured policy framework will be essential for achieving long-term sustainability and success in supercomputing initiatives.

4. Looking ahead, India must focus on achieving exascale computing, incorporating quantum computing advancements, and developing energy-efficient, green supercomputing technologies to remain competitive on the global stage. This will require stronger research collaborations, targeted funding for next-generation computing technologies, and well-defined national strategies. It is also crucial to expand HPC applications across critical sectors such as healthcare, agriculture, financial services, and smart city planning, ensuring that the benefits of supercomputing are widely distributed across industries.

5. NSM has already positioned India as a major player in global supercomputing, but more steps are required to unlock its full potential. The recommendations outlined in this dissertation seek to drive technological self-reliance, global competitiveness, and broader societal benefits. By focusing on continuous innovation, improved governance, and

strategic investments, NSM can serve as a key enabler of India's scientific, industrial, and economic growth. With a well-defined roadmap and a commitment to excellence, India's supercomputing ecosystem can evolve into a world class network that not only meets domestic needs but also contributes significantly to international advancements in high-performance computing. This executive summary provides an overview of the dissertation's key themes and serves as a strategic guide for policymakers, researchers, and industry leaders in shaping the future trajectory of India's supercomputing mission.

## **Chapter 1 : Introduction**

1. **Overview of High-Performance Computing (HPC) and Its Global Significance.** High-performance computing (HPC) has emerged as a cornerstone of scientific discovery and technological innovation in the 21<sup>st</sup> century. It powers advancements across critical fields, including climate modelling, drug discovery, artificial intelligence, and material science (Goyal, Singh, & Sharma, 2019). HPC systems have enabled the researchers to process large amounts of data, simulate complex phenomena, and speed up innovation. Globally, various nations invest greatly in HPC infrastructure to maintain competitiveness, foster innovation, and address serious societal challenges. The amalgamation of HPC with emerging technologies such as artificial intelligence (AI) and big data analytics has further expanded its applications, making it essential for national development and international collaborations (Ministry of Science & Technology, 2020).
2. Leading economies such as the United States, China, Japan, and the European Union have significantly advanced their supercomputing capabilities by developing exascale computing systems, which can perform a quintillion calculations per second. These systems are critical for breakthroughs in various fields, including national security, advanced engineering, and personalised medicine (Kaur & Malhotra, 2022). Given the increasing reliance on HPC for economic and technological growth, India has recognised the need to build its own high-performance computing ecosystem to stay competitive globally.
3. **Introduction to the National Supercomputing Mission (NSM) and Its Relevance to India.** Considering the strategic importance of HPC, the Government of

India launched the National Supercomputing Mission (NSM) in 2015. The mission is a collaborative initiative led by the Department of Science and Technology (DST) and the Ministry of Electronics and Information Technology (MeitY), with implementation partners such as the Centre for Development of Advanced Computing (C-DAC) and the Indian Institute of Science (IISc) (MeitY, 2023), using imported components to fully indigenous design and production. Key installations under the mission, such as PARAM Siddhi-AI and Pratyush, have significantly enhanced India's computational capabilities. These systems support critical research areas, including weather prediction, bioinformatics, artificial intelligence, and cyber security. Additionally, the mission aims to bridge the gap between academia and industry by providing HPC infrastructure to universities, research labs, and enterprises, ensuring that India's scientific community has access to world-class computing resources (C-DAC, 2024).

4. **Research Problem, Objectives, and Significance of the Study.** Despite significant progress, the NSM faces several challenges that limit its full potential. These include the underutilisation of supercomputing resources due to a shortage of skilled professionals, continued reliance on imported hardware, and gaps in coordination among stakeholders (Sharma, Malhotra, & Singh, 2019). Addressing these issues is crucial to maximising the mission's impact and achieving its long-term objectives.

5. This study aims to document the progress of the NSM from 2015 to 2024, focusing on its achievements, challenges, and areas for improvement. The research objectives include:-

- (a) To analyse the development of HPC infrastructure under NSM.
- (b) To evaluate the mission's contributions to research and human resource

development.

(c) To identify challenges and propose actionable recommendations for enhancing its effectiveness.

(d) To assess the impact of NSM in fostering innovation and scientific breakthroughs within Indian research institutions.

(e) To explore how NSM has influenced India's computational self-reliance and its alignment with national strategic initiatives (Singh, Sharma, & Malhotra, 2020).

6. By providing a comprehensive account of the NSM's journey, the study seeks to inform policymakers, researchers, and stakeholders about its role in advancing India's scientific and technological capabilities. The findings of this research could contribute to shaping future policy directions for supercomputing in India.

7. **Scope, Limitations and Delimitations of the Research.** The scope of this study is to document and analyze the progress of the National Supercomputing Mission from 2015 to 2024. It examines the mission's achievements in infrastructure development, research output, and human resource training, along with the challenges encountered during implementation. The research relies on publicly available data sources, including government reports, academic publications, and industry analyses (IIPA, 2024).

8. Key limitations include:-

(a) Reliance on secondary data, as primary data collection (e.g., surveys or interviews) is not within the study's scope.

(b) Focus on the Indian context, excluding comparative analyses with global

HPC initiatives.

(c) The study is limited to developments up to 2024 and does not consider subsequent advancements or policy changes.

(d) Possible information gaps due to restricted access to confidential reports and industry-specific evaluations (MeitY, 2023).

9. These delimitations ensure the research remains focused and manageable while providing valuable insights into the NSM's progress.

10. **Structure of the Dissertation.** The dissertation is organised into the following chapters:-

(a) **Introduction.** Provides an overview of HPC, introduces the NSM, outlines the research problem and objectives, and defines the scope and structure of the study.

(b) **Literature Review.** Summarises existing research on HPC and NSM, identifies gaps, and highlights the significance of the mission.

(c) **Research Methodology.** Describes the quantitative approach adopted, data sources used, and methods of analysis.

(d) **Documentation of NSM's Progress.** Details the mission's achievements, including infrastructure development, research contributions, and training initiatives.

(e) **Challenges and Gaps in NSM.** Analyses of key challenges faced during the implementation of the mission, including underutilisation, skill shortages, and dependency on foreign technology.

(f) **Opportunities for Future Growth.** Explores strategies for addressing

challenges and enhancing the mission's effectiveness, with a focus on policy recommendations and advancements in indigenous supercomputing technology.

(g) **Conclusion**. Summarises findings, discusses implications, and offers recommendations for future research and policy.

11. This structured approach ensures a comprehensive and logical exploration of the National Supercomputing Mission and its impact on India's high-performance computing landscape. By thoroughly documenting NSM's progress, this study aims to contribute to the ongoing discourse on the role of supercomputing in India's scientific and technological advancement.

## **Chapter 2 : Literature Review**

1. **Introduction.** This chapter provides a comprehensive review of existing literature on high-performance computing (HPC) and the National Supercomputing Mission (NSM) in India. The purpose of this review is to establish the foundational knowledge required to assess the progress, challenges, and future opportunities of the NSM. The chapter is structured into sections that cover the historical evolution of HPC, an overview of NSM, India's supercomputing initiatives, NSM's progress and key achievements, the impact of NSM on research and industry, and identified gaps in the current body of knowledge.
2. **Evolution of High-Performance Computing (HPC).** High-performance computing has played a transformative role in scientific and industrial advancements globally. The development of supercomputing can be traced back to the 1960s, with the introduction of vector processing systems and later, massively parallel processing architectures (Dongarra et al., 2020). Today, HPC is widely used in climate modelling, genomics, artificial intelligence, and complex engineering simulations (Kaur & Malhotra, 2022). The rise of exascale computing, capable of performing a quintillion calculations per second, has further pushed the boundaries of computational science (Borkar, 2021). Countries such as the United States, China, and Japan have heavily invested in HPC, recognizing its role in economic and technological leadership.
3. **Overview of the National Supercomputing Mission (NSM).** The National Supercomputing Mission (NSM) was launched in 2015 as a collaborative initiative between the Department of Science and Technology (DST) and the Ministry of Electronics and Information Technology (MeitY), with implementation by the Centre for

Development of Advanced Computing (C-DAC) and the Indian Institute of Science (IISc). NSM aims to create a self-reliant HPC ecosystem by designing, developing, and deploying indigenous supercomputers across various academic and research institutions in India (MeitY, 2023). The mission's objectives include:

- (a) Enhancing computational capabilities for scientific research and industrial applications.
- (b) Reducing dependency on foreign supercomputing technologies.
- (c) Training a workforce proficient in HPC and its applications.
- (d) Strengthening India's position as a global player in supercomputing research and innovation.

4. **India's Supercomputing Initiatives and NSM's Achievements.** India's engagement with supercomputing began in the late 1980s with the establishment of C-DAC and the development of the PARAM series supercomputers (MeitY, 2023). The NSM represents a structured effort to enhance India's computational capabilities through a phased approach, which includes:

- (a) **Phase 1.** Acquisition of supercomputers from global markets and setting up facilities in premier institutions.
- (b) **Phase 2.** Integration of domestically manufactured components into supercomputing systems.
- (c) **Phase 3.** Complete indigenisation of supercomputers and the development of indigenous microprocessors.

5. Under NSM, India has successfully deployed over 22 supercomputers in academic and research institutions, with PARAM Siddhi-AI, Pratyush, and Mihir among the most

powerful systems in the country. PARAM Siddhi-AI was ranked among the top 100 supercomputers globally in 2020 (C-DAC, 2024). The mission has also facilitated over 200 HPC-based research projects, leading to advancements in climate modelling, bioinformatics, drug discovery, and artificial intelligence applications (IIPA, 2024). Additionally, the mission has trained over 22,000 students and researchers, thereby contributing to the expansion of India's HPC expertise.

6. Several notable projects have benefited from NSM, including:
  - (a) **Weather and Climate Prediction**. Supercomputers viz Pratyush and Mihir have considerably improved India's capabilities in monsoon and cyclone forecasting.
  - (b) **Drug Discovery and Genomics**. PARAM Siddhi-AI has been used in molecular simulations for pharmaceutical research, accelerating drug discovery efforts.
  - (c) **Artificial Intelligence and Machine Learning**. HPC resources are leveraged for deep learning and AI-based applications in sectors such as healthcare, agriculture, and financial modelling.
  - (d) **Defence and Space Research**. Supercomputing capabilities have been used for ballistic missile simulations, satellite data analysis, and aerospace engineering.

7. **Impact of NSM on Research and Industry**. NSM has significantly contributed to advancing India's computational research landscape. The supercomputers deployed under the mission have enabled groundbreaking research in weather forecasting, bioinformatics, and material science (Singh, Sharma, & Malhotra, 2020). Further, NSM

has also facilitated training programs that benefited thousands of researchers, towards development of a skilled workforce for HPC applications (IIPA, 2024). Despite these advancements, full utilisation of these supercomputing resources remains a challenge (Goyal, Singh, & Sharma, 2019). Various industries such as pharmaceuticals, automobile engineering, and aerospace have also started leveraging supercomputing facilities to enhance product design and development processes, so as to improve efficiency and innovation (MeitY, 2023). While some industries have adopted HPC, gap still exists in its widespread adoption across various sectors due to awareness and accessibility challenges.

8. **Challenges and Gaps in the Literature.** Although NSM has made significant strides, a number of challenges persist. The reliance on imported components, limited domestic manufacturing capabilities, and skill shortages are important concerns (Borkar, 2021). Additionally, literature review highlights that India's supercomputing infrastructure is underutilized primarily due to gaps in user training and lack of awareness about HPC applications in various fields (Kaur & Malhotra, 2022). Although global comparisons indicate that India is progressing steadily through NSM, more research is needed on ways to enhance its competitiveness on an international scale (Sharma et al., 2019). There is also a lacunae of literature addressing the long-term sustainability of NSM and strategies for ensuring continued advancements in HPC beyond its planned phases.

9. **Conclusion.** This chapter reviewed existing literature on high-performance computing and the National Supercomputing Mission in India. It highlighted the evolution of HPC, the significance of NSM, its achievements, impact on research and industry, and the challenges that need to be addressed. The findings underscore the need

for continued investments in indigenous HPC development, workforce training, and enhanced utilisation strategies. The next chapter will outline the research methodology employed in this study.

### **Chapter 3 : Research Methodology**

1. **Introduction.** This chapter outlines the research methodology adopted for the study, providing a structured approach to examining the progress, achievements, and challenges of the National Supercomputing Mission (NSM). The methodology is designed to ensure a rigorous and objective assessment using quantitative data analysis techniques. This chapter includes an overview of the research approach, data sources, analytical methods, and the justification for the chosen methodology.
  
2. The methodology ensures that the research remains data-driven, transparent, and replicable. Considering the scope of this study, an empirical evaluation of NSM's progress will be undertaken maintaining alignment with the study's objectives.
  
3. **Overview of the Quantitative Approach.** A quantitative research approach has been adopted for this study to systematically analyze the progress and impact of the NSM. Quantitative research allows for the collection, organization, and interpretation of numerical data, facilitating an objective assessment of measurable indicators related to supercomputing infrastructure, utilisation, and research outputs (Creswell & Creswell, 2018). The study primarily focuses on analyzing secondary data sources that provide quantifiable metrics regarding NSM's achievements.
  
4. The key aspects of the quantitative approach used in this study include:
  - (a) **Descriptive Analysis.** Used to summarize and present key facts regarding NSM's progress in terms of the number of supercomputing installations, computational power enhancement, and research contributions.

- (b) **Trend Analysis**. Applied to evaluate the growth of HPC infrastructure and the increasing adoption of supercomputing facilities over different phases of NSM.
  - (c) **Comparative Analysis**. Although the study does not directly compare NSM with global benchmarks, comparisons within different phases of NSM implementation provide insights into its evolution.
  - (d) **Correlation Analysis**. Examined relationships between investments in NSM and subsequent research productivity, innovation, and industrial applications of HPC.
5. By applying these analytical techniques, the study seeks to derive meaningful insights into the effectiveness and efficiency of the NSM's implementation.
6. **Description of Data Sources**. This study relies entirely on secondary data sources that provide verified and publicly available information on the NSM. The key data sources used for this research include:
- (a) **Government Reports and Policy Documents**.
    - (i) Ministry of Electronics and Information Technology (MeitY) Annual Reports (MeitY, 2023).
    - (ii) National Supercomputing Mission (NSM) progress reports by C-DAC (C-DAC, 2024).
    - (iii) Policy papers and official statements from the Department of Science and Technology (DST) (DST, 2023).
    - (iv) Budget allocations and expenditure reports relevant to NSM implementation (IIPA, 2024).

- (b) **Academic Studies and Research Publications.**
  - (i) Peer-reviewed journal articles analyzing the impact of NSM on research and industry (Goyal, Singh, & Sharma, 2019).
  - (ii) Studies on high-performance computing (HPC) trends in India and globally (Kaur & Malhotra, 2022).
  - (iii) Evaluations of NSM's contribution to scientific advancements and computational research (Singh et al., 2020).
- (c) **Industry Publications and Technical Reports.**
  - (i) Reports from C-DAC detailing the performance and utilisation of deployed supercomputers (C-DAC, 2024).
  - (ii) White papers and industry analyses discussing the role of HPC in various sectors such as pharmaceuticals, climate science, and artificial intelligence (IIPA, 2024).
  - (iii) Reports from research organizations detailing collaborative projects involving NSM resources (Sharma et al., 2019).
- (d) **Publicly Available Data and News Articles.**
  - (i) Articles from credible news agencies covering NSM developments (Ministry of Science & Technology, 2020).
  - (ii) Reports from international organizations monitoring India's progress in supercomputing (Borkar, 2021).
  - (iii) Open-access datasets related to HPC deployment and research collaborations (Dongarra et al., 2020).

7. By incorporating these diverse sources, the study ensures comprehensive coverage of NSM's progress and impact.

8. **Explanation of Data Analysis Methods.** Given the quantitative nature of this study, the following data analysis methods are employed:

(a) **Descriptive Statistics.** The study utilises descriptive statistics to quantify key performance indicators of NSM, such as the number of supercomputers deployed, petaflop capacity achieved, and the number of research projects facilitated by NSM resources (MeitY, 2023).

(b) **Trend Analysis.** This method helps in identifying patterns over time, such as the increase in computational power and expansion of supercomputing facilities across institutions (C-DAC, 2024).

(c) **Categorical Data Analysis.** Examines the distribution of NSM resources among different research domains, identifying key areas where HPC has been most utilized (IIPA, 2024).

(d) **Regression Analysis.** Evaluates the potential relationship between government funding, computational advancements, and research output in key scientific disciplines (Sharma et al., 2019).

9. Each of these methods contributes to a systematic evaluation of NSM's success in meeting its objectives and highlights potential areas for further enhancement.

10. **Conclusion.** This chapter detailed the research methodology used to evaluate the National Supercomputing Mission. By employing a structured quantitative approach, this study ensures an objective assessment of NSM's progress, achievements, and challenges. The combination of descriptive, trend, and regression analysis ensures that the research remains data-driven and analytically rigorous. The next chapter will document and analyze the progress made under NSM, using the data and methods outlined in this section.

## **Chapter 4 : Documentation of NSM's Progress**

1. **Introduction.** The National Supercomputing Mission (NSM) has played a pivotal role in transforming India's high-performance computing (HPC) ecosystem. The evolution of supercomputing capabilities in India under the National Supercomputing Mission (NSM) has been transformational, marking a significant leap in computational power, technological self-reliance, and research facilitation. The mission has facilitated the deployment of cutting-edge high-performance computing (HPC) systems, enabling India to address complex scientific challenges, boost industrial applications, and strengthen national security (MeitY, 2023).

2. This chapter comprehensively documents NSM's progress from 2015 to 2024, structured under four key pillars:-

- (a) Infrastructure Development
- (b) Research & Development Contributions
- (c) Applications Developed
- (d) Human Resource Development

### **Infrastructure Development**

3. During the initial years of NSM, India's supercomputing infrastructure was largely dependent on foreign-built systems, with limited indigenous participation in hardware and software development (IIPA, 2024). However, since then, NSM has not only expanded computational power but has also focused on indigenous hardware development, ensuring long-term sustainability and reducing dependence on external sources (C-DAC, 2024).

4. **Milestones in Supercomputing Capacity Expansion.** NSM has significantly strengthened India's supercomputing infrastructure by installing high-performance computing systems across academic and research institutions (Sharma, Malhotra, & Singh, 2019). The supercomputing capabilities have grown from 6.8 petaflops in 2019 to over 24 petaflops in 2024, and the mission has set an ambitious roadmap for the coming years:-

(a) **2015-2019.** Establishment of foundational HPC infrastructure through the deployment of imported supercomputing systems. Key installations included Pratyush and Mihir, focused on weather and climate modelling (Sharma, Malhotra, & Singh, 2019).

(b) **2019-2022.** Transition towards indigenous development, with the PARAM series of supercomputers integrated into premier institutions such as IITs, IISc, and national research laboratories (Goyal, Singh, & Sharma, 2019).

(c) **2022-2024.** Integration of AI-driven computing, quantum computing, and energy-efficient supercomputing, making India a strong contender in the global HPC landscape (Singh, Sharma, & Malhotra, 2020).

5. **List of Supercomputers Deployed Under NSM.** A critical success factor of NSM has been the strategic deployment of supercomputers across academic, research, and industrial institutions, ensuring optimal utilisation and accessibility. The list of Supercomputers deployed under the project is placed at *Appendix 'A'*.

6. **Key Achievements in Supercomputing Infrastructure.**

(a) Deployment of over 24 supercomputers across premier institutions.

- (b) The combined computational capacity of these systems has grown from **6 petaflops in 2019** to **over 24 petaflops by 2024**, positioning India as a significant player in global HPC rankings (C-DAC, 2024).
- (c) Development of indigenous processors (like PARAM Shakti and PARAM Siddhi-AI).
- (d) HPC installations in multiple IITs, IISc, and national research laboratories.
- (e) Expansion of supercomputing access to non-traditional domains, including agriculture, healthcare, and fintech.

7. **Development of Petaflop Supercomputers.** One of the most significant milestones of NSM has been the development of indigenous petascale supercomputers under the PARAM series. The key innovations in this domain include:-

- (a) **PARAM Siddhi-AI.** Ranked among the top 100 supercomputers worldwide, PARAM Siddhi-AI has been instrumental in AI-driven research, deep learning applications, and large-scale simulations.
- (b) **Pratyush & Mihir.** Installed at the Indian Institute of Tropical Meteorology (IITM) and the National Centre for Medium-Range Weather Forecasting (NCMRWF), these supercomputers have enhanced India's climate modelling and weather forecasting capabilities (MeitY, 2023).
- (c) **PARAM Shivay, PARAM Sanganak, and others.** Established at IITs and national research laboratories, supporting diverse applications including computational chemistry, genomics, and space research (IIPA, 2024).

8. **Planned Future Expansions in HPC Capacity.** NSM has outlined plans to further expand India's computational capabilities. The mission aims to achieve 50 petaflops of computing power through:-

- (a) Deployment of additional indigenous supercomputers.
- (b) Increased integration of quantum computing and AI-driven HPC applications.
- (c) Expansion of HPC resources for industry and startups to boost innovation and economic growth (MeitY, 2024).
- (d) Deployment of India's first exascale system by 2030, enhancing global competitiveness in HPC (C-DAC, 2024).
- (e) Expansion of supercomputing applications to newer domains, including precision agriculture, materials science, and personalized medicine.

9. **System Uptime and CPU/ GPU Utilisation.** Performance efficiency is a crucial metric for evaluating the success of deployed HPC systems. The supercomputers commissioned under NSM exhibit high system uptime and utilisation rates, reflecting their consistent reliability and effective workload distribution.

- (a) **System Uptime.** Maintained at an average of 95%, ensuring uninterrupted access for research and industrial applications.
- (b) **CPU Utilisation.**
  - (i) **Average CPU utilisation:** 75-85%
  - (ii) **Peak CPU workloads observed in:** Weather modelling, material sciences, and AI-driven analytics.
- (c) **GPU Utilisation.**
  - (i) **Average GPU utilisation:** 65-80%

- (ii) **Peak GPU applications include:** Deep learning simulations, molecular docking in drug discovery, and cryptographic computations.

10. **International Collaborations in Supercomputing.** India has actively engaged in international collaborations to enhance its supercomputing expertise. Some key partnerships include:-

- (a) **India-USA Collaboration.** Joint research initiatives with U.S. institutions for AI-based supercomputing applications and weather modelling (Borkar, 2021).
- (b) **India-France Partnership.** Development of HPC applications in space research and satellite data analytics.
- (c) **India-Japan Cooperation.** Exchange programs focused on semiconductor technologies and next-generation processors (MeitY, 2023).
- (d) **BRICS Supercomputing Network.** A collaborative initiative to promote HPC research and data-sharing among BRICS nations (IIPA, 2024).

11. These collaborations have provided access to cutting-edge technology, facilitated skill exchange programs, and enhanced India's capability to develop indigenous supercomputing technologies.

12. **Key Industry Partners.** The NSM has actively collaborated with leading industry players and technology providers to ensure cutting-edge advancements in supercomputing hardware and software. These partnerships have strengthened indigenous technological capabilities and promoted innovation in India's HPC landscape (IIPA, 2024).

- (a) **Centre for Development of Advanced Computing (C-DAC)**. Lead implementing agency, responsible for system integration, software optimisation, and HPC infrastructure development.
- (b) **Intel, NVIDIA, AMD**. Primary suppliers of processors and GPUs, ensuring high-performance computing capabilities.
- (c) **Tata Consultancy Services (TCS), Wipro, and Infosys**. Engaged in HPC-driven AI research, financial modelling, and cloud-based analytics.
- (d) **HCL Technologies**. Supporting the indigenisation of software and application optimisation for HPC systems.
- (e) **Multiple startups and SMEs**. Contributing to HPC hardware design, cooling technologies, and quantum computing integration.

13. The infrastructure development under NSM has established India as a serious player in the global HPC ecosystem. The steady expansion of computing power, transition towards indigenous technology, and strategic industry collaborations has positioned India for continued growth and innovation. Moving forward, the development of exascale computing, quantum-driven HPC solutions, and enhanced industrial applications will be critical in ensuring that India remains competitive in the supercomputing domain.

### **Research & Development Contributions**

14. The National Supercomputing Mission (NSM) has played a critical role in advancing scientific research and technological innovation in India. The deployment of supercomputing resources has enabled researchers to tackle complex computational problems across multiple disciplines, including climate science, material engineering,

healthcare, artificial intelligence, agriculture, and multilingual technology development. This section elaborates on the key contributions of NSM in the research and development ecosystem.

15. **Scientific Research Enabled by NSM.**

(a) **Climate Modelling & Weather Forecasting**

(i) Supercomputers Pratyush and Mihir have significantly improved India's capability to predict extreme weather events, reducing disaster response times and enhancing monsoon forecasting accuracy (MeitY, 2023).

(ii) High-resolution simulations have contributed to long-term climate impact assessment and policy planning (IIPA, 2024).

(b) **Drug Discovery & Genomic Research**

(i) PARAM Siddhi-AI has been instrumental in genomic sequencing and drug molecule simulations, accelerating the discovery of potential treatments for diseases (Singh, Sharma, & Malhotra, 2020).

(ii) Computational biology techniques using HPC have led to advancements in personalized medicine and vaccine development.

(iii) AI-driven predictive models for early disease detection and drug interaction analysis have been developed using NSM resources.

(c) **Aerospace & Defence Simulations**

(i) NSM-enabled research has facilitated missile trajectory analysis, aircraft design optimisations, and satellite launch simulations (C-DAC, 2024).

(ii) Advanced materials research for hypersonic vehicle development has been significantly enhanced through HPC modelling (Sharma et al., 2019).

(iii) Computational fluid dynamics (CFD) simulations have contributed to enhanced aerodynamic designs and fuel efficiency improvements.

(d) **Artificial Intelligence & Machine Learning**

(i) HPC clusters have enabled the development of deep learning models for natural language processing, fraud detection, and autonomous vehicle simulations (Borkar, 2021).

(ii) AI applications powered by NSM resources have contributed to smart city planning and energy-efficient infrastructure designs (MeitY, 2023).

(iii) Development of multilingual machine translation systems and text-to-speech models for Indian languages to bridge the digital divide.

(iv) HPC-assisted image and video processing models have enhanced facial recognition, medical imaging, and security applications.

(e) **Automotive Research & Industry Innovations**

(i) High-performance computing has been leveraged for vehicle crash simulations, electric vehicle battery optimisation, and fuel efficiency studies.

(ii) AI-assisted traffic management systems have been developed using NSM resources to improve urban mobility and reduce congestion.

(f) **Agriculture & Environmental Studies**

(i) Climate simulations have helped predict crop yield variations and soil moisture levels, supporting precision farming initiatives.

(ii) AI-based models for pest detection, irrigation management, and climate-resilient crop development have been powered by HPC resources.

(g) **Healthcare & Medical Imaging**

(i) HPC-driven AI models have enabled faster disease diagnostics, enhanced radiological imaging, and real-time analysis of patient health data.

(ii) AI-enhanced tools have assisted in cancer detection, ophthalmology research, and genomic data analysis.

16. **Collaborations & Research Output.**

(a) **International Partnerships.** India has collaborated with France, the USA, and Japan to share expertise in quantum computing, semiconductor research, and climate modelling.

(b) **Research Publications.** Since the launch of NSM, over 5,000 research papers citing NSM-supported computational resources have been published in reputed journals (IIPA, 2024).

(c) **Patent Filings.** NSM-backed projects have resulted in the filing of over 150 patents in domains such as materials science, cryptography, medical imaging, and AI-driven analytics (MeitY, 2023).

(d) The list of applications, tools and programming models developed for AI and HPC is placed at *Appendix 'B'*.

17. The National Supercomputing Mission has significantly contributed to India's research and development ecosystem by providing computational capabilities that empower scientific discovery, industrial innovation, and national security. The advancements made under NSM have not only strengthened India's position in global

high-performance computing but have also enabled indigenous technological development. The continued expansion of HPC infrastructure, combined with AI-driven research, will further drive breakthroughs in healthcare, environmental science, aerospace, and digital transformation. As India moves towards the exascale computing era, strategic investments in cutting-edge research, industry collaborations, and talent development will be essential in sustaining and enhancing the impact of NSM on national progress.

### **Applications Developed**

18. The National Supercomputing Mission (NSM) has enabled the development of advanced computing applications across multiple sectors, including healthcare, climate science, national security, finance, and artificial intelligence (AI). These applications have significantly improved decision-making, predictive analysis, and technological advancements, reinforcing India's position in high-performance computing (HPC).

19. **Healthcare and Medical Research.** Supercomputing has been instrumental in transforming healthcare by enabling advanced research, simulations, and AI-driven diagnostics.

(a) **Genomics and Drug Discovery.** PARAM Siddhi-AI has been used for large-scale genomic sequencing to accelerate the discovery of drug molecules for diseases such as cancer and neurodegenerative disorders (MeitY, 2023).

(b) **Medical Imaging and AI-Based Diagnostics.** HPC-driven AI models have enhanced MRI, CT scans, and radiological analysis, improving early diagnosis and treatment planning (Singh, Sharma, & Malhotra, 2020).

- (c) **Epidemiological Modelling.** Supercomputing resources have helped simulate pandemic spread scenarios, supporting policy decisions during COVID-19 and future infectious disease outbreaks (IIPA, 2024).
20. **Climate Science and Environmental Research.** Supercomputing under NSM has improved India's ability to tackle climate-related challenges through advanced simulations and predictive analytics.
- (a) **Weather and Cyclone Forecasting.** Supercomputers Pratyush and Mihir have significantly improved monsoon and cyclone predictions, reducing economic and human losses (C-DAC, 2024).
- (b) **Climate Change Impact Analysis.** High-resolution models simulate long-term climate change scenarios, **aiding** in global and national policy formulation.
- (c) **Air Pollution and Environmental Monitoring.** AI-driven climate models provide real-time air quality forecasting, crucial for urban planning and public health (Sharma et al., 2019).
21. **National Security and Defence Applications.** HPC has been leveraged for national security, strategic defence simulations, and space exploration.
- (a) **Missile and Ballistic Simulations.** HPC-based trajectory modelling has enhanced missile development, ensuring accuracy and efficiency in defence strategy.
- (b) **Cybersecurity Applications.** AI-driven cyber threat detection and encryption mechanisms have been implemented to counter national security risks.
- (c) **Satellite and Aerospace Research.** Supercomputing is used to analyze satellite imagery, supporting space missions and defence operations (MeitY, 2023).

22. **Artificial Intelligence (AI) and Machine Learning (ML) Applications.** NSM has significantly advanced AI-driven research and computing, supporting multiple industries and governance models.

(a) **Multilingual Speech Processing.** AI-based speech-to-text models have been developed for Indian languages, aiding education, governance, and accessibility.

(b) **Smart Cities and Urban Planning.** AI-powered supercomputing models optimise traffic management, waste disposal, and infrastructure development.

(c) **Agriculture and Precision Farming.** AI-driven weather models and crop yield predictions support precision agriculture and irrigation management (Borkar, 2021).

23. **Financial Sector and Big Data Analytics.** HPC has strengthened India's financial and banking sector through high-speed data processing and fraud detection mechanisms.

(a) **High-Frequency Trading Models.** AI-driven HPC frameworks enhance financial risk analysis and algorithmic trading.

(b) **Fraud Detection Systems.** Supercomputers analyze large volumes of banking transactions in real time to prevent cyber fraud.

(c) **Blockchain and Secure Transactions.** Cryptographic models developed using HPC improve the security of financial transactions (IIPA, 2024).

24. **Energy and Renewable Resource Optimisation.** Supercomputing has played a key role in energy optimisation, resource allocation, and renewable energy development.

- (a) **Power Grid Optimisation.** AI-driven models predict power demand fluctuations to optimise electricity grids and energy storage.
- (b) **Renewable Energy Forecasting.** Supercomputers analyze solar and wind energy outputs, improving renewable energy integration into the grid.
- (c) **Nuclear Energy Simulations.** High-performance computing assists in nuclear reactor simulations, improving safety and efficiency.

25. **Earthquake Simulation and Disaster Management.** NSM has enabled seismic activity analysis and disaster preparedness simulations, helping India enhance its disaster response.

- (a) **Earthquake and Tsunami Prediction Models.** HPC-based simulations analyze seismic activity patterns, aiding early warning systems (MeitY, 2023).
- (b) **Landslide and Flood Risk Mapping.** AI-powered terrain analysis models help predict landslides, floods, and natural disasters in vulnerable regions.
- (c) **Emergency Response Planning.** AI-driven simulations optimise disaster response strategies, improving evacuation plans and resource deployment (Sharma et al., 2019).

26. **Space and Astrophysics Research.** HPC has contributed significantly to space exploration, astrophysical research, and planetary modelling.

- (a) **Black Hole and Cosmic Evolution Simulations.** Supercomputers model gravitational waves, neutron star collisions, and black hole formations.

- (b) **Satellite Trajectory Optimisation.** High-precision trajectory calculations **improve India's** space exploration missions and satellite launches (C-DAC, 2024).
- (c) **Radio Astronomy Data Processing.** HPC processes large-scale cosmic data, enabling breakthroughs in radio astronomy and deep-space exploration.

27. The applications developed under the National Supercomputing Mission have led to transformative advancements across multiple sectors, enhancing India's technological, economic, and strategic capabilities. From healthcare diagnostics to space research, AI-driven decision-making to disaster preparedness, NSM has played a pivotal role in modernizing India's computational landscape. Moving forward, investments in AI-HPC integration, energy-efficient computing, and exascale supercomputing will further strengthen India's position as a global leader in high-performance computing.

### **Human Resource Development**

28. The National Supercomputing Mission (NSM) has significantly contributed to human resource development (HRD) by nurturing a skilled workforce equipped with advanced knowledge in high-performance computing (HPC), artificial intelligence (AI), and data science. The mission focuses on empowering researchers, scientists, engineers, and students through structured training programs, collaborative academic partnerships, and international exchanges. This section outlines the initiatives, partnerships, and achievements that have shaped the growth of India's supercomputing talent pool.

29. **Skill Development and Training Programs.** One of NSM's pivotal objectives is to build a robust HPC-skilled workforce by providing specialised training and capacity-building programs:

- (a) **Basic and Advanced HPC Training.** The NSM has conducted over 500 workshops and training sessions, training more than 22,000 individuals in HPC skills across India (MeitY, 2023).
- (b) **AI and Data Science Training.** Advanced training modules focusing on AI, deep learning, and data analytics have been introduced, particularly in collaboration with premier research institutions (IIPA, 2024).
- (c) **Inclusive Training Programs.** Free HRD courses have been provided for women and underprivileged individuals, fostering an inclusive approach to technological empowerment.
- (d) **Online Certification Courses.** Platforms such as SWAYAM and NPTEL offer online courses on supercomputing fundamentals, AI integration with HPC, and quantum computing applications.

30. **Academic Collaborations.** NSM has established collaborations with leading national and international academic institutions to foster HPC research and education:

- (a) **IITs and IISc.** HPC centers at IITs (Kharagpur, Roorkee, Gandhinagar) and IISc Bangalore serve as training hubs for cutting-edge supercomputing research (C-DAC, 2024).
- (b) **International Collaborations.** Academic exchange programs with universities in the United States, Japan, and France facilitate cross-border research, sharing advancements in quantum computing and AI-driven applications (Sharma et al., 2019).

(c) **Specialised Research Fellowships.** The NSM supports PhD students and postdoctoral researchers through dedicated HPC research fellowships. Over 1,680 PhD students from 150+ institutes have utilized supercomputing infrastructure for their research.

31. **Industry Partnerships for Workforce Development.** NSM has partnered with major industry players to bridge the gap between academia and industrial applications:

(a) **Collaborations with Tech Giants.** Partnerships with companies such as Intel, NVIDIA, AMD, TCS, and Wipro have enabled joint training sessions and technology transfer.

(b) **Start-Up and MSME Support.** Initiatives like PARAM Utkarsh and PARAM AIRAWAT AI support startups and MSMEs by providing access to advanced computing infrastructure and specialised training (MeitY, 2023).

(c) **Industry-Academia Interface.** Programs focusing on industrial training internships help integrate theoretical research with practical industry needs.

32. **Government-Led Initiatives for Human Capital Development.** Government-backed programs have played a vital role in nurturing India's supercomputing talent pool:

(a) **National HPC Curriculum Development.** Introduction of HPC and AI courses across Indian universities to mainstream supercomputing education.

(b) **Skill India and Digital India Initiatives.** Integrated with NSM to promote digital literacy and create a technologically adept workforce.

(c) **National Fellowship Schemes.** Specialised fellowships have been launched to support research in HPC, AI, quantum computing, and machine learning.

33. **Impact of NSM on India's Talent Pool.** The NSM has significantly advanced India's expertise in high-performance computing, creating a new generation of skilled researchers and professionals:

- (a) **Training Reach.** Over 22,000 individuals have been trained in HPC skills since the NSM's inception (MeitY, 2023).
- (b) **User Base.** More than 8,000 active users, including 1,680 PhD students from 150+ institutes across India, have engaged with the NSM supercomputing infrastructure.
- (c) **Research Output.** Execution of over 93 lakh jobs on supercomputing infrastructure has resulted in the publication of more than 1,000 research papers.
- (d) **Inclusive Growth.** NSM's commitment to inclusivity is reflected in offering free HRD courses to women and underprivileged individuals, promoting equal access to technological education.
- (e) **International Recognition.** Indian researchers have contributed to globally recognized HPC and AI research projects, establishing India as an emerging leader in supercomputing talent development.

34. The NSM has laid a solid foundation for the development of a technologically skilled workforce in India. Through its emphasis on training, research collaboration, international partnerships, and inclusivity, NSM has fostered a dynamic ecosystem of innovation and research excellence. Moving forward, sustained investments in capacity-building initiatives and a stronger focus on interdisciplinary education will further enhance India's global standing in the realm of supercomputing and advanced research.

## **Fund Allocation and Utilisation**

35. Since its inception in 2015, the National Supercomputing Mission (NSM) has received substantial financial allocations to enhance India's high-performance computing (HPC) infrastructure. The financial framework of NSM reflects a strategic approach to national technological self-reliance while addressing challenges in global competitiveness.

36. **Analysis of Fund Allocation and Utilization Trends.** The NSM follows a structured implementation strategy divided into three distinct phases, each with specific objectives and financial outlays. The phase wise budget allocation and utilization trends are covered below: -

(a) **Phase 1 (2016-2020): Establishing Basic Infrastructure.**

- (i) **Allocated Budget:** ₹1,600 crore (C-DAC, 2022, p. 12)
- (ii) **Utilization:** ₹1,248 crore (78%) by March 21 (MeitY,2021,para 6)
- (iii) **Focus Areas:**
  - Setting up initial HPC infrastructure in premier institutions
  - Laying the foundation for indigenous supercomputing development
  - Training technical personnel in supercomputing operations

(b) **Phase 2 (2020-2023): Scaling Capacity and Indigenisation.**

- (i) **Allocated Budget:** ₹2,300 crore (DST, 2020, p. 3)
- (ii) **Utilization:** ₹1,426 crore (62%) as of March 23 (MeitY,21,para. 6)
- (iii) **Focus Areas:**

- Enhancing computational capacity with indigenous supercomputers
  - Developing India's first indigenous HPC processors
  - Strengthening academic and research collaborations
- (c) **Phase 3 (2023-2026): Advancing Towards Exascale Computing.**
- (i) **Allocated Budget:** ₹3,000 crore (MeitY, 2023, p. 15)
- (ii) **Focus Areas:**
- Building **Exascale Computing** capabilities
  - Enhancing the **indigenous content** of supercomputers to 80%

37. **Cumulative Expenditure (as of March 2023).** The fund allocation has been structured so as to address four key pillars of India's HPC ecosystem. A breakdown of cumulative expenditure across these categories is as follows:-

<b><u>Category</u></b>	<b><u>Amount (₹ crore)</u></b>	<b><u>% of Total</u></b>
Infrastructure	1,892	68%
R&D	562	20%
HR Development	326	12%
Total	2,780	100%

*Source: Compiled from C-DAC (2023) and MeitY (2023)*

38. **Key Infrastructure and Technological Outcomes.** The effective utilisation of funds under NSM is evident in the following strategic outcomes:-

- (a) **Deployment of Supercomputers.** The NSM has led to the deployment of 33 supercomputers across premier academic and research institutions. As of

December 2023, the total installed compute capacity reached 24 PetaFlops, with major installations including:-

- (i) **PARAM Siddhi-AI (5.26 PetaFlops)**. Deployed at C-DAC, Pune, one of India's most powerful AI-driven supercomputers.
  - (ii) **PARAM Brahma (3.3 PetaFlops)**. Installed at IISER Pune, supporting climate modelling and materials research.
  - (iii) **PARAM Shivay (1.67 PetaFlops)**. Deployed at IIT-BHU, catering to HPC applications in engineering and physics.
- (b) By November 2024, additional deployments increased total compute capacity to 32 PetaFlops across 33 institutions, with a total financial outlay of ₹1,874 crore. This reflects an increase of ₹655.86 crore in expenditure between December 2023 and November 2024, supporting the deployment of 13 additional supercomputers.
- (c) **4.2 Indigenous Development and Self-Reliance**. A major focus of NSM has been on reducing reliance on imported technology. Key achievements include:-
- (i) Increasing indigenous content from 30% in Phase 1 to 60% in Phase 2.
  - (ii) Development of India's first HPC server "Rudra" and its deployment in NSM-funded supercomputers.
  - (iii) Integration of Shakti microprocessors in select HPC nodes, paving the way for fully indigenous systems.
- (d) **Human Resource Development**. The development of a skilled workforce is critical for maximizing supercomputing utilization and fostering future innovation in India's HPC landscape.
- (i) Training programs conducted: 142

- (ii) Total professionals trained: more than 22000
- (iii) Academic partnerships: 38 institutions have integrated HPC curriculum into their coursework.

39. **Challenges in Fund Utilization and Infrastructure Deployment.** Despite substantial financial investment and progress, several challenges persist in fund utilization and infrastructure deployment:-

- (a) **Dependence on Imported Components.** 65% of supercomputing components (such as processors and memory modules) are still imported, leading to high costs and supply-chain vulnerabilities.
- (b) **Utilisation Gaps and Operational Bottlenecks.** 40% of deployed supercomputing resources operate below 70% efficiency, indicating scope for better workload optimization and resource sharing.
- (c) **Delays in Procurement and Deployment.** The average procurement cycle for supercomputing hardware is 18 months, leading to delays in system commissioning and operational readiness.

40. **Future Roadmap and Financial Strategy**

- (a) **Increasing Indigenous Technological Capability.** NSM aims to achieve 80% indigenous content in its supercomputers by 2026, focusing on domestic manufacturing of HPC processors and interconnects.
- (b) **Development of Exascale Computing.** India plans to develop an Exascale prototype by 2025, which will mark a significant leap in computational capacity, surpassing 1,000 PetaFlops.

(c) **Expansion of Human Resource Training Programs.** The mission targets training 25,000 professionals by 2026, ensuring a sustainable talent pool for future supercomputing applications.

(d) **Strengthening Public-Private Partnerships (PPP).** Financial incentives, tax subsidies, and research grants will be introduced to attract private investment in India's HPC ecosystem, reducing dependency on government funding.

41. The financial structuring and expenditure trends under NSM indicate significant progress in supercomputing infrastructure, indigenous capability development, and human resource training. The mission has successfully deployed state-of-the-art HPC systems, yet import dependence and operational inefficiencies remain key challenges. Moving forward, a stronger focus on indigenous technology development, public-private partnerships, and efficient fund utilization will be critical to achieving India's ambition of becoming a global leader in high-performance computing and AI-driven research.

42. **Future Directions in Fund Allocation.** With India's ambition to develop exascale supercomputers and further indigenous technological advancements, continued investment in HPC infrastructure and talent development will be crucial. Strengthening public-private partnerships, optimizing fund distribution, and expanding research collaborations will ensure sustained growth in India's supercomputing capabilities.

43. **Conclusion.** The NSM has made remarkable strides in developing India's supercomputing ecosystem, enhancing computational capacity, and supporting cutting-edge research. The documented growth in infrastructure, funding allocation, and scientific output underscores the mission's success. However, addressing resource underutilisation,

increasing industry participation, and sustaining financial support will be crucial for future advancements. The next chapter will explore the challenges and gaps in NSM implementation and propose recommendations for strengthening India's supercomputing ecosystem.

## **Chapter 5 : Innovations and Indigenous Development**

1. The National Supercomputing Mission (NSM) has been instrumental in driving technological innovation and fostering indigenous development in India's high-performance computing (HPC) landscape. With the goal of making India self-reliant in supercomputing technology, the NSM has focused on building domestic capabilities in hardware, software, and advanced computing applications. This chapter highlights the key innovations, indigenous technology advancements, and collaborative initiatives that have shaped India's journey towards technological sovereignty.

2. **Indigenous Hardware Development.** One of the central objectives of the NSM has been to develop indigenous supercomputing hardware:

(a) **PARAM Series of Supercomputers.** The development of the PARAM series, including PARAM Shivay, PARAM Siddhi-AI, PARAM Brahma, and PARAM Shakti, represents India's growing capacity in designing and deploying homegrown supercomputing systems (C-DAC, 2024).

(b) **AUM Processor Development.** A significant milestone under the NSM is the creation of India's indigenous AUM processor, designed using cutting-edge 5nm technology. This processor is tailored for AI and HPC applications and reflects India's progress toward self-sufficiency in semiconductor technology (MeitY, 2023).

(c) **High-Speed Interconnects and Accelerators.** Development of indigenous interconnect technologies and accelerators to improve data transfer speeds and computational efficiency within supercomputing systems (Goyal, Singh, & Sharma, 2019).

3. **Indigenous Software and Application Development.** In addition to hardware innovations, the NSM has fostered the development of indigenous software ecosystems:

(a) **AI and Machine Learning Frameworks.** Development of AI platforms tailored for Indian languages, including multilingual machine translation systems and text-to-speech synthesis (Singh, Sharma, & Malhotra, 2020).

(b) **Customized Programming Models.** Development of indigenous programming frameworks and tools that optimise the performance of HPC applications for Indian use cases (IIPA, 2024).

(c) **Scientific Simulation and Modelling Software.** Creation of software applications for climate modelling, drug discovery, and astrophysical simulations specifically designed for Indian research institutions (Sharma et al., 2019).

4. **National-Level Solutions and Applications.** NSM has contributed significantly to addressing national challenges through innovative HPC applications:

(a) **Weather Modelling and Climate Prediction.** Enhanced predictive models for monsoon forecasting, cyclone tracking, and climate impact analysis (MeitY, 2023).

(b) **Urban and Disaster Management.** AI-driven urban planning models, earthquake simulations, and disaster response planning tools developed using indigenous technologies (IIPA, 2024).

(c) **Precision Agriculture.** AI-powered models for crop yield forecasting, pest detection, and irrigation management aimed at boosting agricultural productivity (Singh et al., 2020).

5. **Support for Startups, MSMEs, and Academia.** NSM has played a pivotal role in fostering innovation through collaborations with startups, MSMEs, and academic institutions:

- (a) **PARAM AIRAWAT AI and PARAM Utkarsh.** These platforms support startups and MSMEs by providing access to advanced computing infrastructure and fostering innovation in AI-driven applications (C-DAC, 2024).
- (b) **Academic Collaborations.** Partnerships with premier institutions like IITs, IISc, and NITs for research and development in HPC and AI (MeitY, 2023).
- (c) **Funding and Research Grants.** Providing financial assistance and research grants to promote indigenous research and technological development (IIPA, 2024).

6. **International Collaborations and Technological Exchanges.** While prioritizing indigenous development, NSM has also facilitated global partnerships to enhance India's technological capabilities:

- (a) **Collaborations with France, Japan, and the USA.** Joint research projects focusing on quantum computing, AI innovation, and advanced HPC technologies (Goyal et al., 2019).
- (b) **Technology Exchange Programs.** Knowledge-sharing initiatives to strengthen India's expertise in cutting-edge supercomputing technologies (Sharma et al., 2019).

7. **Achievements and Significant Contributions.** The NSM has led to numerous notable achievements that highlight India's growing technological prowess:

- (a) Development of PARAM Siddhi-AI, ranked among the top 100 supercomputers globally (MeitY, 2023).
- (b) Advancement in indigenous AI technologies addressing societal challenges like healthcare, education, and urban development (Singh et al., 2020).
- (c) Establishment of a robust ecosystem for developing indigenous software and hardware solutions (IIPA, 2024).

8. **Concluding Remarks.** The National Supercomputing Mission has successfully laid the groundwork for indigenous technological advancements in India's HPC sector. Through a combination of innovative hardware, homegrown software applications, and strategic collaborations, NSM has propelled India towards achieving technological self-reliance. As the mission moves forward, the focus will remain on enhancing indigenous capabilities, fostering cutting-edge innovations, and driving India's leadership in the global supercomputing landscape.

## **Chapter 6 : Challenges and Gaps**

1. Despite the remarkable progress of the National Supercomputing Mission (NSM), several challenges have hindered its ability to fully realize its objectives. While India has made significant strides in enhancing its high-performance computing (HPC) capabilities, gaps in infrastructure utilisation, dependency on foreign hardware, skill shortages, and coordination among stakeholders remain prevalent (MeitY, 2023; IIPA, 2024). This chapter provides an in-depth analysis of these challenges and identifies the key gaps that need to be addressed for the NSM to achieve its full potential.

2. **Challenges in Utilising Supercomputing Infrastructure.** One of the most pressing issues faced by NSM is the under-utilisation of supercomputing infrastructure. Despite successfully installing high-capacity supercomputers across various research institutions, the mission has struggled to ensure optimal utilisation of these resources (Singh, Sharma, & Malhotra, 2020).

(a) **Resource Under-utilisation.** Utilisation rates for Central Processing Units (CPU) and Graphics Processing Units (GPU) across several institutions remain below optimal levels. For example, reports suggest that some facilities operate at less than 50% CPU capacity, while GPU utilisation often remains under 30%, limiting the full potential of advanced computational tasks (MeitY, 2023). In contrast, global benchmarks indicate that leading HPC centers, such as the Oak Ridge National Laboratory (USA) and RIKEN Center for Computational Science (Japan), achieve utilisation rates above 85% through dynamic resource allocation and AI-driven job scheduling.

(b) **Technical Barriers.** Challenges in job scheduling involve inefficient algorithms that lead to longer queue times for running simulations. Issues in resource allocation include unequal distribution of computing power across institutions, which affects performance optimisation. In addition, limited expertise in workload balancing prevents institutions from maximizing computational power. AI-driven workload management, such as Google's Borg and Kubernetes-based HPC frameworks, could enhance efficiency. Additionally, containerised HPC environments like Singularity and workload schedulers like Slurm have been successfully implemented in leading HPC facilities to improve utilisation (Goyal, Singh, & Sharma, 2019).

(c) **Limited Industry Participation.** Despite significant potential, supercomputing applications in industries like automotive design, financial modelling, and healthcare diagnostics remain underutilised. Industry collaborations are hampered by limited awareness and accessibility challenges (MeitY, 2023).

3. **Dependency on Foreign Hardware and Efforts Toward Indigenisation.** In the initial phases of NSM, there was a substantial reliance on imported hardware and software components:-

(a) **Foreign Dependency.** A significant portion of supercomputing hardware, including processors, GPUs, and interconnects, was sourced from international suppliers. This reliance poses a risk of supply chain disruptions, especially in light of evolving geopolitical tensions (IIPA, 2024).

(b) **Scale of Indigenisation.** The development of the AUM-HPC processor marked a major milestone, but only a fraction of deployed supercomputing infrastructure is powered by indigenous hardware. Current efforts have achieved

approximately 30% indigenisation, with plans for scaling up in upcoming phases of NSM (MeitY, 2023). A comparative analysis with global processors such as AMD EPYC and Intel Xeon shows that AUM-HPC currently lags in floating-point performance and cache efficiency. Furthermore, India faces semiconductor bottlenecks, including limited foundry capabilities and high-speed interconnect alternatives such as InfiniBand, which are still largely imported.

(c) **Challenges in Supply Chain Resilience.** Indigenous production of critical components such as accelerators and memory units remains limited, necessitating robust manufacturing ecosystems and partnerships (Goyal et al., 2019).

4. **Skill Shortages and Their Impact on Effective HPC Utilisation.** The shortage of skilled HPC professionals continues to be a barrier for maximizing supercomputing capabilities (Singh et al., 2020):

(a) **Lack of Specialised Training.** While over 22,000 individuals have been trained under NSM initiatives, advanced skills in areas like parallel programming, GPU-based computation, and quantum simulation remain limited (MeitY, 2023).

(b) **Limited Academic Programs.** Only a handful of institutions in India offer dedicated curricula focusing on HPC, AI, and data-intensive research, which limits the development of specialised expertise (IIPA, 2024). Introducing dedicated HPC-focused degree programs and open-source training in CUDA, MPI, and OpenMP would significantly enhance technical capabilities. Collaborations with global supercomputing centers such as the Texas Advanced Computing Center (TACC) or Europe's PRACE initiative can provide hands-on training and exchange programs.

(c) **Impact on Utilisation.** Skill shortages impact critical sectors like genomics research, climate simulation, and industrial automation, restricting NSM's broader societal contributions (Sharma et al., 2019).

5. **Gaps in Policy Implementation and Coordination Among Stakeholders.**

Effective policy implementation and stakeholder coordination continue to present challenges (Sharma et al., 2019). The NSM aimed to coordinate HPC efforts nationwide, focusing on infrastructure development, application support, human resource development, and research and development. However, India does not have standardised state-wise High-Performance Computing (HPC) policies to mitigate disparities:-

(a) **Lack of Clear Governance Structure.** There is a need for a centralised governing body that can streamline communication between academic institutions, government bodies, and industry partners (IIPA, 2024). Establishing a National HPC Regulatory Authority could help standardise policies and funding mechanisms across states.

(b) **Inconsistent Policy Execution.** Implementation of HPC policies varies significantly across states and institutions, leading to uneven development in infrastructure and research priorities (MeitY, 2023). Standardised state-wise HPC policies would help mitigate these disparities. Individual states have initiated their own strategies to attract technology investments. For instance, Karnataka has introduced incentives to double the number of Global Capability Centres (GCCs) by 2029, including measures such as rent reimbursements and patent fee concessions. However, these initiatives primarily target broader technology and semiconductor sectors rather than focusing specifically on HPC.

(c) **Alignment with National Priorities.** A coordinated effort is needed to align supercomputing resources with strategic national goals such as energy security, defence research, and healthcare innovation (Singh et al., 2020). Public-Private Partnership (PPP) models should be explored to expand HPC industry adoption, leveraging private sector expertise in cloud-based supercomputing services.

6. Despite its achievements, the National Supercomputing Mission faces several challenges that hinder its full potential. Addressing underutilisation of computational resources, enhancing CPU and GPU usage efficiency, reducing reliance on foreign hardware, and fostering indigenous innovation are crucial steps toward realizing the NSM's objectives. Moreover, bridging skill gaps and establishing clearer coordination among stakeholders will be essential for strengthening India's HPC ecosystem and driving technological self-reliance (MeitY, 2023).

## **Chapter 7 : Recommendations for Enhanced Effectiveness**

1. The National Supercomputing Mission (NSM) has significantly advanced India's high-performance computing (HPC) capabilities, yet there remain several areas that require strategic interventions to maximize its effectiveness. This chapter provides comprehensive recommendations aimed at addressing challenges related to infrastructure utilisation, indigenisation, skill development, policy implementation, and future growth.

2. **Enhancing Infrastructure Utilisation.** Despite significant investments in supercomputing infrastructure, underutilisation of resources remains a key concern. Optimising the use of HPC resources requires a multi-pronged approach that integrates AI-driven scheduling, real-time monitoring, and cloud-HPC hybrid models to further improve efficiency and accessibility:-

(a) **Improving CPU and GPU Utilisation.**

(i) **Real-time Monitoring Systems.** Deploying AI-powered real time monitoring tools can significantly enhance resource allocation efficiency by identifying bottlenecks, forecasting workload patterns, and automating resource reallocation. Supercomputing centers such as Oak Ridge National Laboratory (ORNL) and Lawrence Livermore National Laboratory (LLNL) have implemented deep learning based anomaly detection systems that predict hardware failures and optimize resource distribution dynamically (Dongarra, 2022).

(ii) **Dynamic Resource Allocation.** Adaptive scheduling mechanisms leveraging machine learning (ML) models can be used to optimise job distribution by analysing historical workload trends and adjusting

CPU/GPU allocation in real time. Slurm and Kubernetes based containerised HPC environments, as seen at National Center for Supercomputing Applications (NCSA) at the University of Illinois, allow institutions to maximise computational throughput while minimising idle time (HPCwire, 2023).

(iii) **Industry Participation**. Facilitating increased collaboration with industries is essential to enhance HPC adoption. Initiatives such as the European High-Performance Computing Joint Undertaking (EuroHPC JU) provide a model where subsidised industry access has led to AI-driven drug discovery, financial modelling, and aerospace simulations. A similar PPP framework in India could encourage private-sector R&D participation in automotive engineering, precision medicine, and climate modeling (MeitY, 2023).

(b) **Optimising Job Scheduling and Resource Allocation**.

(i) **AI-Driven Scheduling Algorithms**. Supercomputing centers are increasingly adopting Reinforcement Learning (RL) based scheduling algorithms to enhance job throughput and reduce queue times. At Berkeley Lab's National Energy Research Scientific Computing Center (NERSC), AI-assisted schedulers have improved task execution rates by 20%, allowing better resource utilisation (NERSC, 2023). In India, C-DAC Pune is exploring similar AI-augmented job management strategies.

(ii) **Cloud Integration for HPC**. Expanding cloud-integrated HPC solutions will enable institutions to scale computational workloads dynamically and reduce hardware dependency. Microsoft Azure's HPC

Cloud, Google Cloud TPU Clusters, and Amazon Web Services (AWS) ParallelCluster provide robust models for integrating cloud with on-premise supercomputers (HPCwire, 2023). A case study from IISc Bangalore demonstrated a 25% increase in compute efficiency when hybrid cloud-based HPC access was introduced for large-scale molecular dynamics simulations (IISc, 2024)..

3. **Case Studies of Efficient HPC Centers.** Leading global and Indian HPC centers have significantly improved utilization through AI-driven scheduling, cloud integration, and dynamic workload balancing: -

- (a) **Oak Ridge National Laboratory (ORNL, USA).** Implemented AI-based workload prediction models, leading to a 30% increase in GPU efficiency.
- (b) **NERSC (USA).** Integrated real-time anomaly detection, reducing system downtime by 40%.
- (c) **EuroHPC JU (EU).** Established industry-academic collaboration models, enabling cross-sectoral utilization of HPC resources.
- (d) **C-DAC Pune (India).** Adopted AI-assisted queue management, improving job scheduling for weather modelling and genomic research.
- (e) **IISc Bangalore (India).** Developed hybrid cloud-HPC frameworks, leading to enhanced accessibility and compute power availability

4. By leveraging these global best practices, India can significantly enhance NSM's efficiency and industry adoption, driving technological self-reliance and innovation in AI, drug discovery, and advanced materials research.

5. **Promoting Indigenisation and Reducing Foreign Dependency.** To enhance India's supercomputing capabilities and reduce reliance on foreign technology, a strategic push towards indigenous hardware and semiconductor manufacturing is essential. The successful development of AUM-HPC processors, the Shakti microprocessor, and the Rudra server architecture marks India's progress, but further efforts are required to achieve self-sufficiency in HPC class processors, accelerators, and interconnects. The following are recommended to strengthen India's domestic supercomputing ecosystem:-

(a) **Strengthening Indigenous Processor and Hardware Development.**

(i) **Comparison of Indigenous Processors with Global Counterparts.** The AUM-HPC processor (developed under NSM) is India's first indigenous hardware at HPC class CPUs, focusing on RISC-V architecture, power efficiency, and workload adaptability (Centre for Development of Advanced Computing [CDAC], 2024). Subsequently, the Shakti processor (developed by IIT Madras) is an open-source RISC-V processor series that provides foundational computing capabilities but lacks high end performance required for supercomputing applications (IIT Madras, 2023). In comparison, AMD EPYC and Intel Xeon processors dominate global HPC systems due to their advanced fabrication nodes (5nm vs. India's 28nm), higher core counts, integrated AI accelerators, and memory bandwidth enhancements (Advanced Micro Devices [AMD], 2023; Intel Corporation, 2023). While India's efforts in RISC-V and ARM-based architectures are commendable, they lag behind global players in terms of transistor density, performance-per-watt efficiency, and interconnect scalability (Ministry of Electronics and Information Technology [MeitY], 2023).

(ii) **Accelerate R&D and Manufacturing for AUM-HPC and Shakti**

**Processors.** Increase investment in the development of high-performance AUM-HPC processors, ensuring they meet global benchmarks in core count, memory bandwidth, and power efficiency (CDAC, 2024). Further, Enhanced collaboration between CDAC, IITs, and private semiconductor firms to refine the Shakti processor architecture for supercomputing workloads is required (IIT Madras, 2023). This is feasible through benchmarking against global leaders such as AMD EPYC and Intel Xeon to ensure indigenous processors match international performance standards in fabrication nodes, transistor density, and AI acceleration (Advanced Micro Devices [AMD], 2023; Intel Corporation, 2023).

(iii) **Developing Indigenous Accelerators and Interconnects.**

Establish an India-specific high-speed interconnect standard to reduce dependency on NVIDIA NVLink, AMD Infinity Fabric, and Intel Omni-Path (Sharma et al., 2019). India has to Leverage Compute Express Link (CXL) and RISC-V interconnect frameworks to develop open source, high performance networking solutions tailored for Indian HPC (Singh et al., 2020). The country also need to encourage domestic startups and research institutions to develop AI accelerators and FPGA-based supercomputing architectures, reducing reliance on NVIDIA CUDA GPUs..

(b) **Addressing Semiconductor Manufacturing Bottlenecks.**

(i) **Challenges in Semiconductor Manufacturing.** India lacks a domestic foundry capable of producing high performance sub 10nm chips required for supercomputing workloads (Carnegie Endowment for

International Peace, 2024). Dependence on TSMC and Samsung for fabrication poses supply chain risks in light of geopolitical tensions (Goyal et al., 2019). Memory modules, high speed NVMe storage, and specialised AI accelerators remain bottlenecks due to limited domestic manufacturing capabilities (IIPA, 2024).

(ii) **Align NSM with India's Semiconductor Mission (ISM)**. India's Semiconductor Mission is focused on building 28nm fabs, but HPC applications demand 5nm or lower for optimal performance and efficiency (MeitY, 2023). Therefore, synergy between NSM and ISM is required to establish a reliable domestic supply of sub 10nm fabrication nodes, essential for high-performance computing (MeitY, 2023). Further, there is a requirement to prioritize investments in advanced chip manufacturing plants (fabs) that can produce memory modules, AI accelerators, and HPC processors, reducing import dependencies (Carnegie Endowment for International Peace, 2024).

(iii) **Expand Public-Private Partnerships (PPPs) for Semiconductor and HPC Growth**. Establish joint ventures between C-DAC, IITs, Indian semiconductor start-ups, and global firms to accelerate domestic chip design and manufacturing (Goyal et al., 2019). Encourage technology transfers and licensing agreements with Taiwan, South Korea, and Japan to acquire expertise in advanced semiconductor fabrication. Promote private sector participation in NSM by offering incentives for HPC-related R&D and supporting fabless semiconductor start-ups.

6. The successful implementation of the AUM-HPC processor, along with other indigenous developments such as the Shakti microprocessor, and Rudra server architecture, showcases India's growing self-reliance in HPC hardware manufacturing. These advancements are key milestones in reducing dependency on foreign technology and strengthening India's supercomputing capabilities.

7. **Bridging Skill Gaps and Expanding HPC Education.** A shortage of skilled professionals in high-performance computing (HPC) remains a significant barrier to maximizing the potential of India's supercomputing infrastructure. To address this challenge and build a sustainable talent pipeline, the following recommendations should be implemented:-

(a) **Establishing Specialised HPC Degree Programs.**

(i) **Integration of HPC into Higher Education.** Premier institutions such as IITs, NITs, IISc, and central universities should launch specialised degree programs in HPC, AI-driven simulations, and quantum computing (MeitY, 2023). These programs should offer interdisciplinary coursework covering parallel programming (CUDA, MPI, OpenMP), AI-HPC integration, big data analytics, and computational modeling (Singh et al., 2020).

(ii) **Industry Oriented HPC Training Tracks.** Develop structured HPC specialisation tracks within existing M.Tech, Ph.D., and executive education programs to ensure students gain both theoretical and applied expertise (CDAC, 2024). Offer elective courses on exascale computing, quantum-HPC integration, and energy-efficient supercomputing using ARM-based architectures and liquid cooling techniques (IIPA, 2024).

- (b) **Strengthening Hands-on Industry Collaborations.**
- (i) **Joint Research and Development (R&D) Programs.** Establish HPC Industry-Academia Research Hubs in collaboration with leading technology firms such as NVIDIA, Intel, AMD, and Tata Consultancy Services (TCS) to provide hands-on training on cutting-edge HPC technologies (Goyal et al., 2019). Facilitate internships and research projects at C-DAC, DRDO, and private-sector AI-HPC labs to bridge the gap between academia and industry.
- (ii) **HPC Apprenticeship and Certification Programs.** Introduce government-backed HPC apprenticeship programs allowing students and early career professionals to work on real world HPC and AI-driven supercomputing projects (Sharma et al., 2019). Expand industry sponsored HPC certification programs focused on AI-HPC workload optimisation, quantum computing simulations, and cloud-HPC hybrid models (Singh et al., 2020).
- (c) **Government Incentives for HPC and Quantum Skill Development.**
- (i) **National HPC and AI-HPC Training Fund.** The government should create a dedicated National HPC and AI-HPC Skill Development Fund under NSM to support scholarships, research grants, and infrastructure upgrades at academic institutions (MeitY, 2023).
- (ii) **Tax Incentives and Funding for HPC Training Centers.** Provide tax breaks and funding incentives for industries and academic institutions that establish specialized HPC and quantum computing training centers

(IIPA, 2024). Develop public-private partnerships (PPPs) to co-fund supercomputing training initiatives, ensuring accessibility for students and professionals.

8. Institutions such as the Indian Institutes of Technology (IITs), the Indian Institute of Science (IISc), National Institutes of Technology (NITs), and specialised research centers like C-DAC and IIIT Hyderabad have integrated HPC-focused curricula. These institutions offer dedicated courses in parallel computing, AI-driven simulations, and quantum computing, leading to an increase in research output in computational sciences and industrial applications. However, a nationally coordinated approach is needed to scale these efforts and align them with global best practices.

9. **Strengthening Policy Implementation and Coordination.**

(a) **Establishing a Centralised Governing Body.**

(i) **Creation of a National HPC Council.** A dedicated governing body should be established to streamline policy implementation and coordinate efforts among various stakeholders, including government agencies, research institutions, and private sector entities (Sharma et al., 2019). This council would oversee national level HPC initiatives, ensure resource optimisation, and develop long term strategies for India's supercomputing ecosystem.

(ii) **Uniform Policy Execution.** Standardised operational guidelines should be developed to ensure uniform adoption and utilisation of NSM resources across different sectors (IIPA, 2024). A structured policy framework will provide clarity on funding mechanisms, infrastructure

sharing protocols, and industry participation, ensuring effective governance of HPC initiatives.

(b) **Fostering Greater Collaboration Among Stakeholders.**

(i) **Industry - Government Research Partnerships.** Strengthening collaboration between the government, academia, and industry is essential to align supercomputing research with national priorities. Public-private partnerships (PPPs) should be encouraged to drive innovation in HPC applications across healthcare, climate modeling, defense, and other critical sectors (Goyal et al., 2019).

(ii) **Incentivising Private Investment.** Financial incentives such as tax breaks, grants, and subsidies should be introduced to attract private technology firms to invest in HPC development in India (MeitY, 2023). Encouraging indigenous startups and multinational corporations to establish R&D centers focused on supercomputing advancements will foster a robust HPC ecosystem.

(c) **Learning from Global Best Practices.**

(i) **Adopting International Models.** The European Union's EuroHPC initiative serves as an exemplary model, fostering collaboration among research institutions and industries through dedicated funding mechanisms and shared computational resources. By implementing joint supercomputing centers that pool resources from multiple nations, the initiative ensures optimised infrastructure utilisation and promotes industry-

academia partnerships to drive cutting-edge innovation in HPC (European Commission, 2023).

(ii) **Facilitating Cross-Border Research Projects.** India should engage in international collaborations by signing research agreements with global supercomputing hubs. Participation in joint projects will enhance knowledge exchange, improve India's HPC capabilities, and provide access to advanced supercomputing technologies and expertise.

10. India can strengthen the governance and coordination of its supercomputing ecosystem, ensuring sustained growth, enhanced industry participation, and global competitiveness in high-performance computing.

11. **Public-Private Partnership (PPP) models to Expand HPC Industry Adoption.**

India has initiated several Public-Private Partnership (PPP) models to expand High-Performance Computing (HPC) industry adoption. These initiatives reflect India's strategic approach to leverage PPP models for expanding HPC infrastructure and industry adoption, and fostering innovation: -

(a) **IndiaAI Mission.** Launched in March 2024, this mission aims to nurture India's AI innovation ecosystem through a PPP model. A key component is the establishment of a state-of-the-art AI compute infrastructure featuring over 18,000 GPUs, developed collaboratively with private sector partners. This initiative underscores the government's commitment to enhancing computational resources and democratizing AI access across various sectors (IndiaAI, 2024; S&P Global, 2024).

(b) **National AI Compute Capacity/ GPU Hubs Development.** In May 2024, a strategy was proposed to scale up India's compute capacity to meet growing local demand. This includes building a national AI compute capacity of at least 10,000 GPUs through PPPs, ensuring affordable and widespread access to computational resources essential for AI development (Carnegie Endowment, 2024).

(c) **GARUDA Grid Initiative.** The GARUDA project is India's grid computing initiative connecting 17 cities and 45 institutes, including IITs and C-DAC centers. This collaboration between government research institutions and the private sector aims to create a nationwide computational grid, enhancing resource sharing and research capabilities across the country (Wikipedia, n.d.).

12. **Future Directions: Towards Exascale Computing and Beyond.** To keep pace with global advancements, India must focus on achieving exascale computing, which involves performance beyond one exaFLOP ( $10^{18}$  calculations per second), and fostering international collaborations:

(a) **Roadmap for Achieving Exascale Computing.**

(i) **Investment in Next-Generation Supercomputers.** Allocate funding for developing exascale supercomputers capable of performing a quintillion ( $10^{18}$ ) calculations per second (CDAC, 2024).

(ii) **Focus on Green Supercomputing.** Promote energy-efficient supercomputing architectures to reduce the carbon footprint of HPC operations (MeitY, 2023). Adopting ARM-based architectures and liquid

cooling techniques can significantly improve energy efficiency, reducing the environmental footprint of HPC systems.

(b) **Quantam – HPC Integration.**

(i) Integrating quantum computing with high-performance computing (HPC) is crucial for further effectiveness of NSM. Quantum-HPC hybrid models can significantly accelerate complex simulations in fields such as materials science, cryptography, and pharmaceutical research, where classical HPC systems face scalability limitations (Preskill, 2018).

(ii) India has taken initial steps in quantum computing through initiatives like the National Quantum Mission (NQM), which aims to develop indigenous quantum technologies, but deeper synergy with NSM is required (MeitY, 2023). Establishing dedicated Quantum-HPC hybrid clusters within existing supercomputing facilities, similar to efforts by IBM, Google, and European HPC centers, can bridge this gap (IBM, 2022). Additionally, fostering collaborations with global quantum computing leaders and investing in indigenous quantum processors will reduce reliance on foreign technology.

(iii) Furthermore, incorporating quantum computing education into NSM training programs will build a skilled workforce capable of leveraging these advancements (Singh et al., 2024). By strategically integrating quantum computing with HPC, India can drive breakthroughs in computational efficiency, secure critical national infrastructure, and advance its scientific and industrial research capabilities, ensuring long-term technological leadership (MeitY, 2023).

13. **Concluding Remarks.** The National Supercomputing Mission (NSM) has positioned India as an emerging leader in HPC, but to achieve its full potential, the mission must focus on improving infrastructure utilisation, strengthening indigenous capabilities, bridging skill gaps, enhancing policy execution, and investing in future advancements. By implementing these strategic recommendations, India can ensure that NSM remains a cornerstone of scientific and industrial progress in the years to come.

## **Chapter 8 : Conclusion and Way Forward**

1. The National Supercomputing Mission (NSM) has played a transformative role in advancing India's high-performance computing (HPC) capabilities. Over the years, it has enabled the deployment of indigenous supercomputers, strengthened research infrastructure, and contributed to industrial and scientific growth. However, the journey towards a self-reliant, globally competitive supercomputing ecosystem is far from over. This chapter consolidates key findings from the study and presents a strategic vision for the future of NSM.

### **Summary of Key Findings**

2. The analysis of NSM's progress, challenges, and gaps highlighted are covered in the succeeding paragraphs.

### 3. **Achievements of NSM.**

(a) Deployment of India's top-tier supercomputers, such as PARAM Siddhi-AI, PARAM Shivay, and PARAM Brahma, positioning India in global HPC rankings.

(b) Development of indigenous HPC technologies, including the AUM-HPC processor, Rudra server architecture, and Shakti microprocessor, reducing foreign dependency.

(c) Expansion of HPC adoption across multiple domains, including weather modelling, drug discovery, precision agriculture, financial modelling, and AI-driven applications.

(d) Establishment of HPC training programs, training over 22,000 professionals, enhancing India's computational research workforce and bridging the skill gap.

(e) Strengthening of public-private partnerships (PPPs) to promote supercomputing research and infrastructure expansion.

4. **Challenges and Gaps Identified.**

(a) Underutilisation of computational resources, with CPU and GPU usage levels remaining suboptimal, primarily due to inadequate training and accessibility barriers.

(b) Continued reliance on foreign hardware and software, despite progress in indigenisation efforts, requiring accelerated R&D investments.

(c) Shortage of skilled professionals to manage and optimise HPC infrastructure, emphasizing the need for curriculum advancements in HPC education.

(d) Inadequate coordination among government agencies, academic institutions, and industry stakeholders, limiting NSM's full impact on national development.

5. **Key Recommendations for Overcoming Challenges.**

(a) **Enhancing Infrastructure Utilisation.** Implementing AI-based workload management, real-time performance monitoring, and cloud-HPC hybrid models to optimise system efficiency.

- (b) **Strengthening Indigenisation.** Scaling up domestic semiconductor manufacturing, investing in indigenous chip fabrication, and expanding research on HPC accelerators.
- (c) **Bridging the Skill Gap.** Establishing more HPC-focused academic programs, specialised research hubs, and incentivizing private-sector training initiatives to increase technical expertise.
- (d) **Improving Policy Execution.** Creating a National HPC Council to streamline governance, ensure transparent implementation of policies, and encourage inter-agency collaboration.

### **Future Vision for NSM**

6. The future of NSM must align with India's long-term vision of becoming a global leader in supercomputing. To achieve this, the mission should focus on the points highlighted in succeeding paragraphs.

### 7. **Strengthening Indigenous HPC Capabilities.**

- (a) Developing India's first exascale supercomputer, capable of a billion-billion ( $10^{18}$ ) calculations per second, enhancing India's global competitive position in HPC.
- (b) Enhancing energy-efficient computing architectures to promote green supercomputing, ensuring sustainable power consumption and environmental responsibility.

(c) Expanding investment in indigenous HPC chip design, fabrication, and AI-driven acceleration technologies to reduce dependency on foreign semiconductor supply chains.

8. **Expanding Research Collaborations.**

(a) Establishing deeper collaborations with leading global supercomputing research institutions such as Oak Ridge National Laboratory (USA), RIKEN (Japan), and the European HPC network.

(b) Encouraging public-private partnerships (PPPs) to drive supercomputing adoption in industries such as automotive, aerospace, pharmaceuticals, and finance.

(c) Strengthening partnerships with India's premier research institutions such as IISc, IITs, NITs, C-DAC, and IIITs, to boost domestic supercomputing capabilities.

9. **Aligning NSM with National Development Goals.**

(a) Expanding HPC applications in national security, defence research, and cyber security to enhance India's strategic capabilities.

(b) Strengthening HPC support for smart cities, sustainable agriculture, and disaster preparedness to improve national resilience.

(c) Promoting AI-powered policy simulations for better governance, enabling data-driven decision-making for socio-economic development.

## **Policy and Strategic Roadmap**

10. For NSM to continue its impact, a comprehensive policy framework and sustained investment strategy must be adopted, as covered in succeeding paragraphs.

### **11. Governance and Regulatory Improvements.**

(a) Establishing a National HPC Council responsible for overseeing all NSM initiatives, coordinating government and private-sector efforts.

(b) Introducing mandatory HPC utilisation audits to assess the effectiveness of deployed resources and optimise system usage.

(c) Implementing standardised protocols for data security, cloud-HPC integration, and AI-powered computational frameworks to ensure compliance with global cybersecurity standards.

### **12. Funding Mechanisms for Sustained Growth.**

(a) Increasing government funding allocation for next-generation supercomputing projects, particularly in quantum computing and AI-driven applications.

(b) Encouraging private sector investments in HPC infrastructure, semiconductor R&D, and AI applications to create a self-sustained ecosystem.

(c) Establishing international funding collaborations to drive joint development of future exascale and post-exascale supercomputers.

### **13. Expanding HPC Applications Across New Domains.**

(a) Supporting HPC-driven research in genomics, materials science, financial analytics, and climate change modelling.

- (b) Promoting AI-integrated supercomputing for autonomous vehicle development, smart grid management, and healthcare diagnostics.
- (c) Facilitating cross-border HPC collaborations, allowing Indian researchers to participate in global projects tackling climate change, space exploration, and pandemic preparedness.

### **Final Thoughts**

14. The National Supercomputing Mission (NSM) has positioned India as a leading force in high-performance computing, but the journey is far from complete. As India moves toward exascale computing, AI-driven supercomputing, and quantum advancements, the need for policy refinement, skill development, and enhanced infrastructure remains critical.

15. By embracing indigenisation, fostering global partnerships, and integrating HPC into national policy frameworks, India can emerge as a global supercomputing powerhouse—not just in terms of computational capacity but also in its ability to drive innovation, research, and technological self-reliance.

16. As NSM progresses into its next phase, a sustained commitment to innovation, efficiency, and collaboration will ensure that India's supercomputing ecosystem remains a cornerstone of its scientific, industrial, and economic future.

17. Additionally, India must proactively address emerging computing paradigms such as quantum computing, neuromorphic architectures, and AI-driven automation, positioning NSM as an enabler of next-generation computational advancements.

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**Appendix 'A'****Refers to Chapter 4 Para 5****SUPERCOMPUTERS DEPLOYED IN INDIA**

1. The following table provides a comprehensive list of supercomputers deployed in India under the National Supercomputing Mission (NSM). It includes details such as location, computational capacity, and the year of installation.

<b>Ser</b>	<b>State/UT</b>	<b>Name of the institution Installed at</b>	<b>Name of Supercomputer</b>	<b>Compute Capacity</b>	<b>Year of Commission</b>
1.	Maharashtra	C-DAC, Pune, National AI Facility	PARAM Siddhi	6.5PF/210PF (AI)	2020
2.	Karnataka	IISc, Bangalore	PARAM Pravega	3.3PF	2022
3.	Maharashtra	IIT Bombay	PARAM Rudra	3 PF	2025
4.	Delhi	Inter-University Accelerator Centre(IUAC), Delhi	PARAM Rudra	3 PF	2024
5.	Karnataka	Jawaharlal Nehru Centre for Advanced Scientific Research(JNCASR), Bangalore	PARAM Yukti	1.8PF	2020
6.	Maharashtra	IISER, Pune	PARAM Brahma	1.7PF	2020
7.	West Bengal	IIT, Kharagpur	PARAM Shakti	1.66PF	2020
8.	Uttar Pradesh	IIT, Kanpur	PARAM Sanganak	1.66PF	2020
9.	Uttarakhand	IIT, Roorkee	PARAM Ganga	1.66PF	2022
10.	Delhi	NIC, Delhi	PARAM System	(50 AI PF/ 1.3 PF)	2024
11.	Maharashtra	Giant Metrewave Radio Telescope (GMRT) - National Centre for Radio Astrophysics, (NCRA), Pune	PARAM Rudra	1.0 PF	2024

12.	Uttar Pradesh	IIT(BHU), Varanasi	PARAM Shivay	838TF	2019
13.	Telangana	IIT, Hyderabad	PARAM Seva	838TF	2021
14.	Punjab	National Agri-Food Biotechnology Institute, Mohali(NABI), Mohali	PARAM Smriti	838TF	2021
15.	Karnataka	C-DAC, Bangalore, National MSME Facility	PARAM Utkarsh	838TF	2021
16.	Gujarat	IIT, Gandhinagar	PARAM Ananta	838TF	2022
17.	Tamil Nadu	NIT, Trichy	PARAM Porul	838TF	2022
18.	Assam	IIT, Guwahati	PARAM Kamrupa	838TF	2022
19.	Himachal Pradesh	IIT, Mandi	PARAM Himalaya	838TF	2022
20.	West Bengal	S. N. Bose National Centre for Basic Sciences, Kolkata	PARAM Rudra	838 TF	2024
21.	Maharashtra	C-DAC, Pune	Bioinformatics R&D Facility	230 TF	2021
22.	Delhi	C-DAC, Delhi	PARAM Rudra	200 TF	2024
23.	Maharashtra	C-DAC, Pune	SANGAM Testbed	150 TF	2017
24.	Maharashtra	C-DAC, Pune	PARAM Shrestha	100 TF	2018
25.	Maharashtra	C-DAC, Pune	PARAM Embrio	100 TF	2020
26.	Maharashtra	C-DAC, Pune	PARAM Neel	100 TF	2020

2. **India's Present Global Ranking in Supercomputing.** As of 2024, India ranks in the top 30 nations globally in terms of high-performance computing capacity. While the country has made significant progress, it still lags behind nations such as the United States, China, Japan, and Germany, which have operational exascale supercomputers exceeding 100 petaflops.

3. **Comparative Global Ranking of India's Supercomputers (2024).** While Indian supercomputers are competitive in select domains such as weather modelling, genomics, and artificial intelligence, achieving exascale computing is crucial for competing with global leaders (C-DAC, 2024).

Supercomputer	Ranking (Global)	Country
Frontier	1 <sup>st</sup>	USA
Fugaku	2 <sup>nd</sup>	Japan
Tianhe-3	3 <sup>rd</sup>	China
Sunway TaihuLight	6 <sup>th</sup>	China
LUMI	7 <sup>th</sup>	Europe
PARAM Siddhi-AI	~80 <sup>th</sup>	India
Pratyush	~100 <sup>th</sup>	India

4. **India's Current Global Position in High-Performance Computing.** As of 2024, India ranks among the top 30 nations in high-performance computing (HPC) capacity. The country has seen a steady improvement in its computational capabilities, with supercomputers such as PARAM Siddhi-AI and Pratyush making notable contributions to India's global standing. However, India still lags behind global leaders such as the United States, China, Japan, and Germany, which have deployed exascale computing systems capable of exceeding 100 petaflops (MeitY, 2024).

- (a) **China.** Leading with multiple exascale supercomputers, such as Sunway TaihuLight and Tianhe-3.
- (b) **United States.** Hosts some of the world's fastest supercomputers, including Frontier and Summit.
- (c) **Japan.** Fugaku, one of the most powerful supercomputers, is instrumental in AI and climate research.
- (d) **India.** While significantly improving its HPC infrastructure, the country is yet to reach the exascale computing milestone.

5. **Future Supercomputing Expansions.** The NSM has outlined ambitious plans for future capacity expansion, aiming to reach 50 petaflops by 2027. Some of the upcoming initiatives include:

- (a) Development of an exascale supercomputer by 2030 with indigenous processors.
- (b) Expansion of HPC facilities across more national institutes and industrial research centers.
- (c) Integration of quantum computing and AI-powered supercomputing applications.

6. These developments are expected to enhance India's global standing in supercomputing and strengthen its research ecosystem.

**Appendix ‘B’****Refers to Chapter 4 Para 16(d)****APPLICATIONS, TOOLS, AND PROGRAMMING MODELS FOR AI AND HPC**

<b>Category</b>	<b>Applications &amp; Tools</b>	<b>Programming Models &amp; Frameworks</b>
<b>AI &amp; Machine Learning</b>	TensorFlow, PyTorch, Keras	CUDA, OpenCL, Apache Spark
<b>Scientific Computing</b>	MATLAB, SciPy, GNU Octave	MPI, OpenMP, Parallel MATLAB
<b>Big Data Analytics</b>	Hadoop, Apache Spark, Dask	MapReduce, Flink
<b>Multilingual NLP</b>	IndicNLP, BERT-Indic, Google’s Translatotron	Fairseq, Transformers by Hugging Face
<b>Medical Imaging</b>	MONAI, ITK-SNAP, 3D Slicer	VTK, SimpleITK
<b>Automotive Research</b>	Ansys Fluent, OpenFOAM, Altair HyperWorks	C++, Python, CUDA
<b>Climate Science</b>	WRF, CDO, NCL	FORTRAN, NetCDF, Python
<b>Quantum Computing</b>	Qiskit, Cirq, PennyLane	Quantum Assembly Languages (QASM)