# Machine learning for operational excellence of industrial complexes supporting net-zero

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# Background

- Large industrial complexes store heaps of valuable operational data that is severely under-utilized to enhance their operational excellence
- Data is the fuel to maintain smart operation of complex industrial processes which are controlled on hyperdimensional input space
- The operation of large industrial complexes is categorized into component, system and strategic level and the performance indicators are either of quantitative or qualitative nature

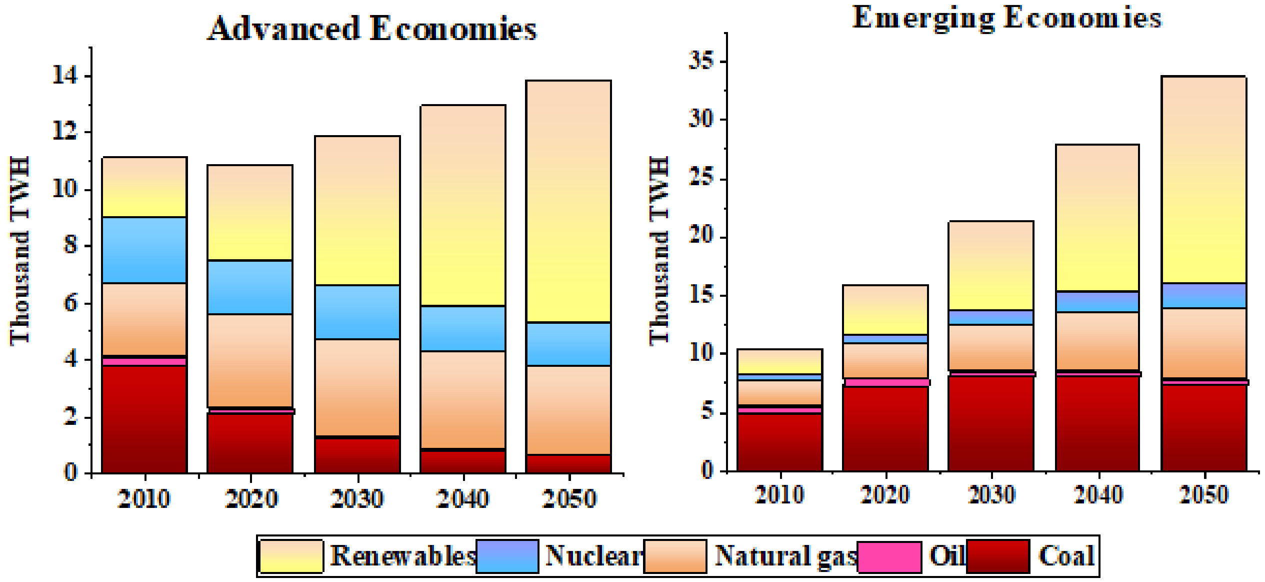
# Background

- The choice of machine learning (ML) model is critical and should be relevant to the nature of problem (quantitative or qualitative)
- A systematic and generic methodology demonstrating the step-wise procedure for reliable implementation of machine learning based analytics is lacking
- Supporting energy efficient operations is critical to contribute to net-zero from the electrical power generation sector which is dominated by fossil fuels for emerging economies (coal causes 40% of global $CO_2$ emissions [1])

[1] IEA, 2021, "An Energy Sector Roadmap to Carbon Neutrality in China;
https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china

# Motivation

- To exploit the true potential of machine learning algorithms for the operational excellence of large-scale industrial complexes including power generation systems
- To contribute to net-zero goal from the energy sector by machine learning



# Challenges for Machine learning driven performance enhancement analytics

- Reliable and efficient utilization of data-driven machine learning analytics for performance enhancement of large industrial complexes is a potential opportunity but it posses challenges:

  (i) Identification of relevant input variables for modelling the system

  (ii) outliers removal and input space visualization

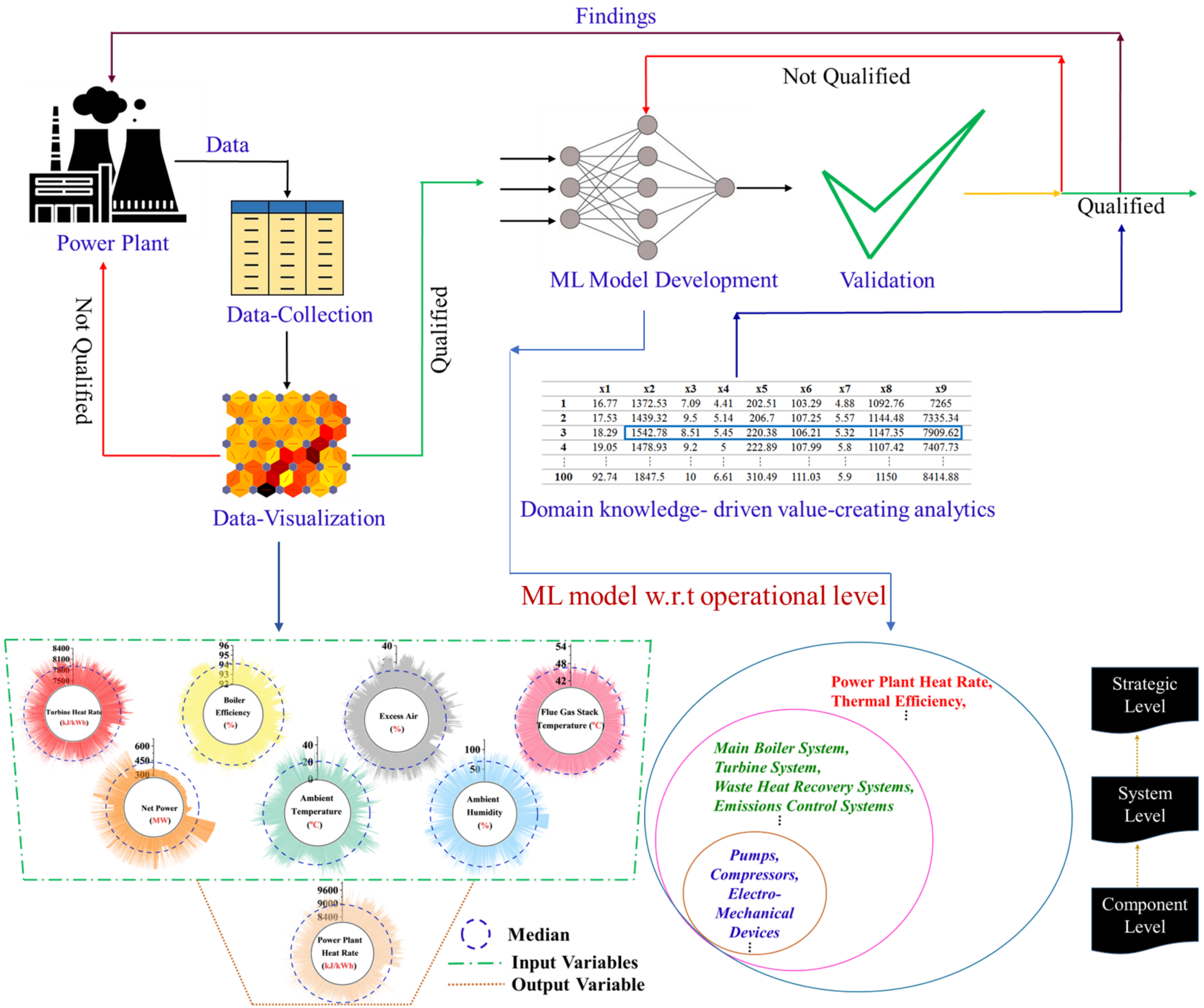
  (iii) selection of ML models w.r.t nature of problem (quantitative or qualitative)

  (iv) sensitivity analysis and domain specific experimental design representing operational scenarios,

  (v) experimental validation and calculating improvements in strategic performance measures of industrial complexes

# Methodology

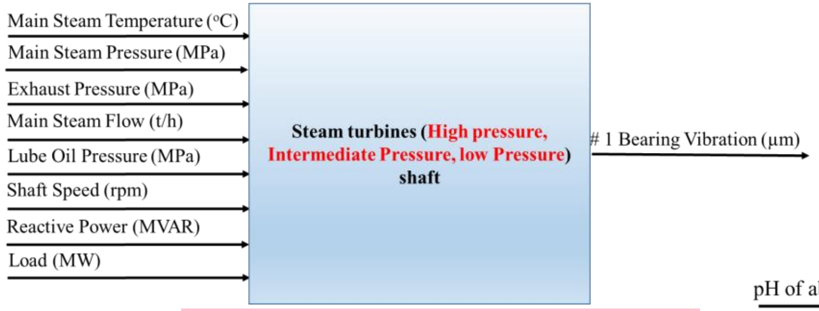
- Variables selection, data-collection and visualization
- Machine learning (ML) model development w.r.t nature of problem and model's validation
- Domain knowledge-driven value creating analytics for operational excellence



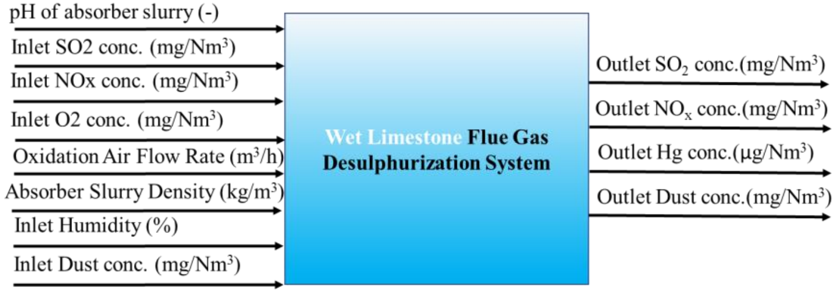

| | x1 | x2 | x3 | x4 | x5 | x6 | x7 | x8 | x9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 16.77 | 1372.53 | 7.09 | 4.41 | 202.51 | 103.29 | 4.88 | 1092.76 | 7265 |
| 2 | 17.53 | 1439.32 | 9.5 | 5.14 | 206.7 | 107.25 | 5.57 | 1144.48 | 7335.34 |
| 3 | 18.29 | 1542.78 | 8.51 | 5.45 | 220.38 | 106.21 | 5.32 | 1147.35 | 7909.62 |
| 4 | 19.05 | 1478.93 | 9.2 | 5 | 222.89 | 107.99 | 5.8 | 1107.42 | 7407.73 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 100 | 92.74 | 1847.5 | 10 | 6.61 | 310.49 | 111.03 | 5.9 | 1150 | 8414.88 |

# Variables selection, Data-collection and Visualization

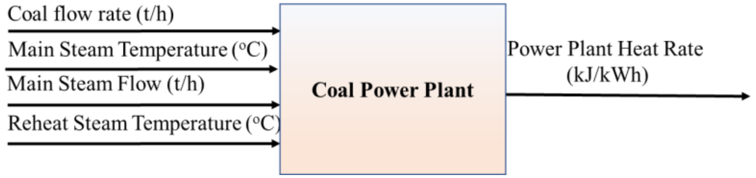
- The operational relevant input variables are identified for the output variable based on domain-knowledge and literature survey




Component-level problem



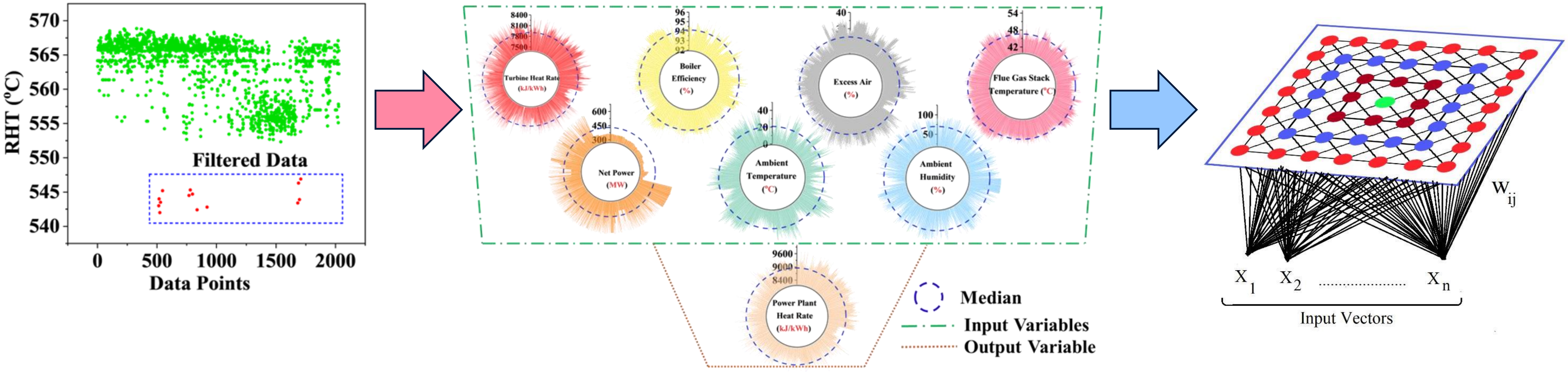

System-level problem




Strategic-level problem

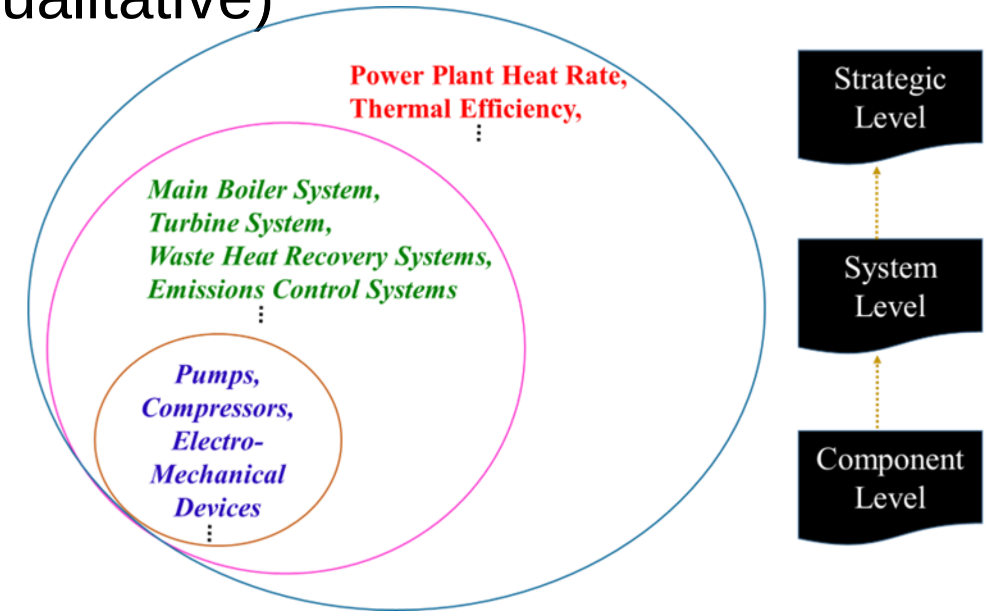
# Parameters selection, Data-collection and Visualization

- Outliers and incorrect observations in the collected data are eliminated, and distribution space is visualized



# Identification of nature of problem and selection of machine learning model

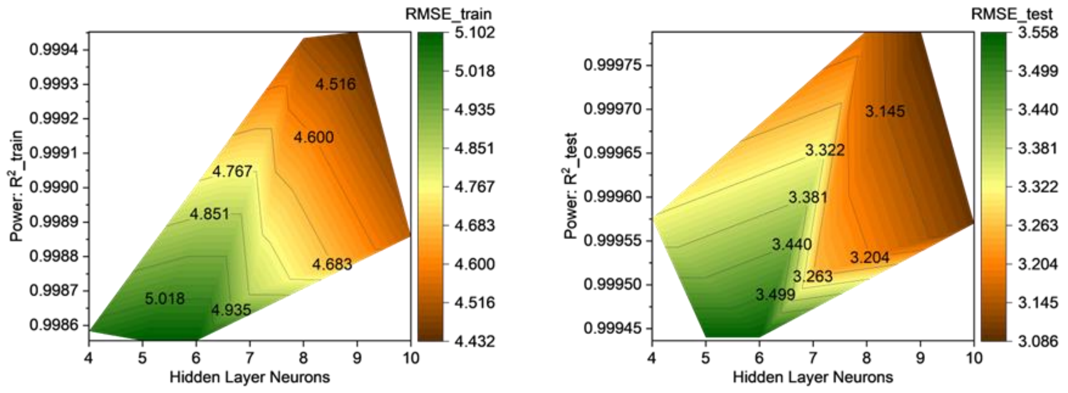
- The operation of large industrial complexes is divided into three levels, component (quantitative), system (quantitative) and strategic (qualitative)




- Component level problem: Analyse #1 bearing vibration of steam turbine shaft bearing (ANN model)
- System level problem: Analyse $SO_2$, Hg, $NO_x$ and Hg emissions from wet limestone flue gas desulphurization system (ANN model)
- Strategic level problem: Analyse thermal efficiency and power generation from coal power plant (SVM)

# Machine learning model development & Validation

- The machine learning model is developed under extensive hyper-parameter tuning

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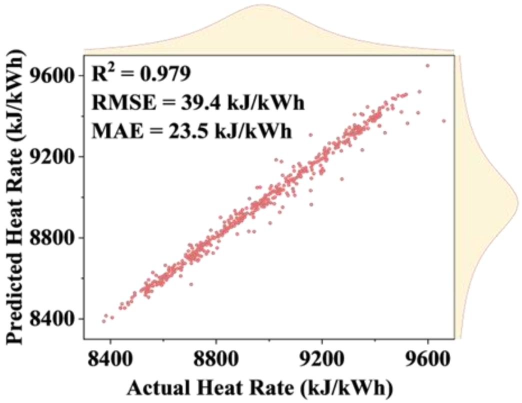
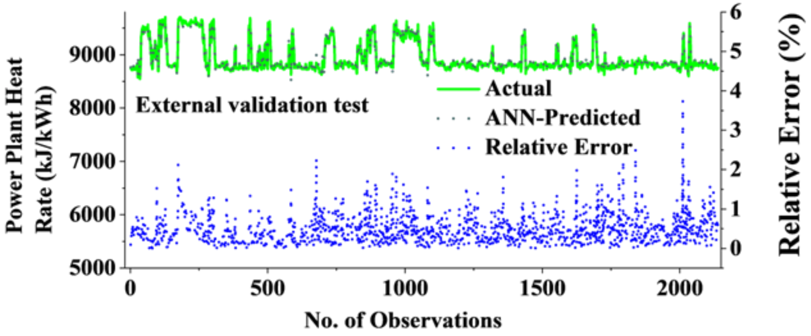
# Machine learning model development & Validation

- The developed model is validated on system representative dataset

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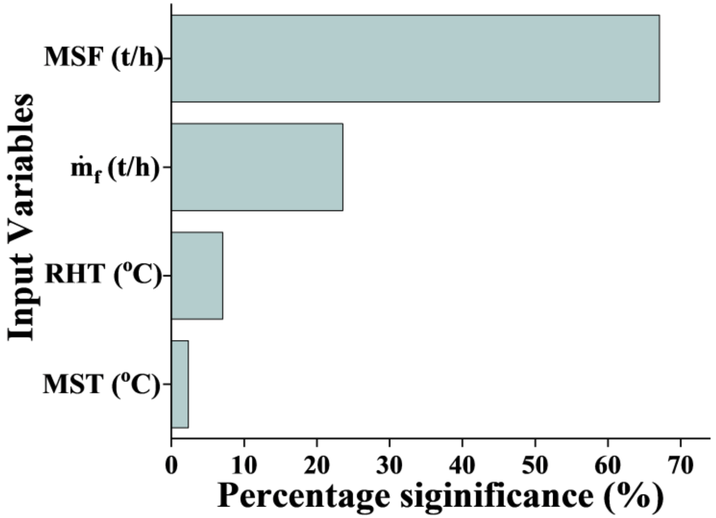
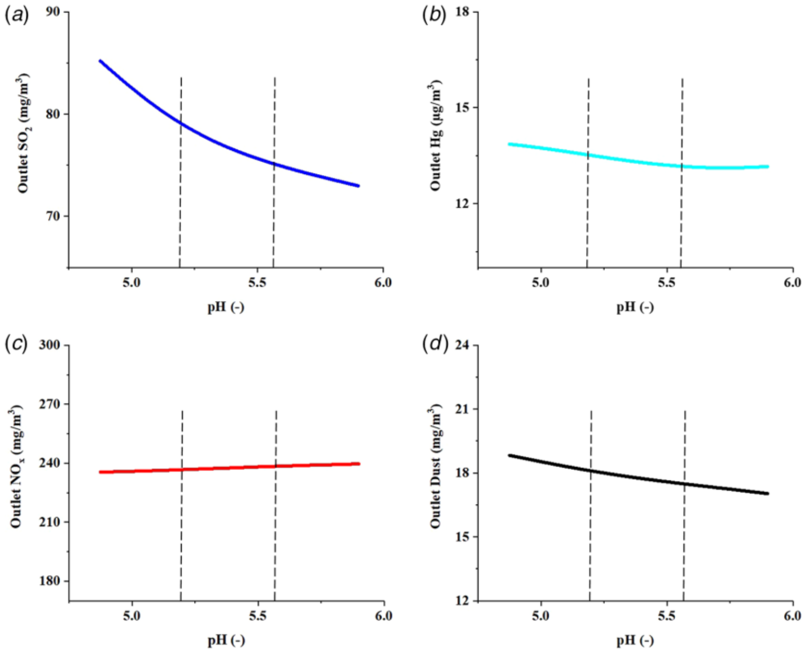
# Variables significance and Parametric Study

- The variables significance is determined by sensitivity analysis techniques: Partial derivative method, Monte Carlo randomization etc.,

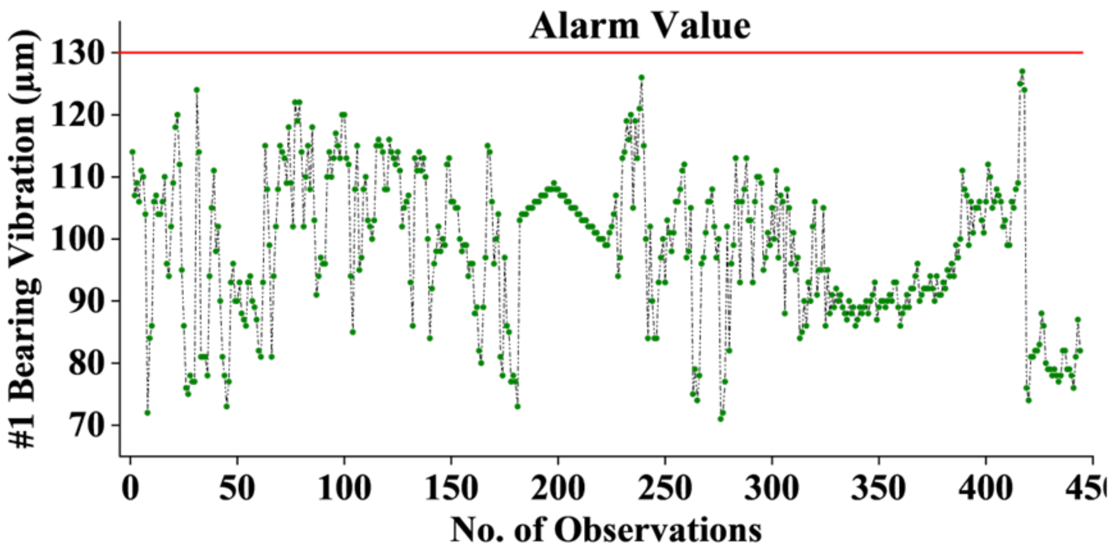


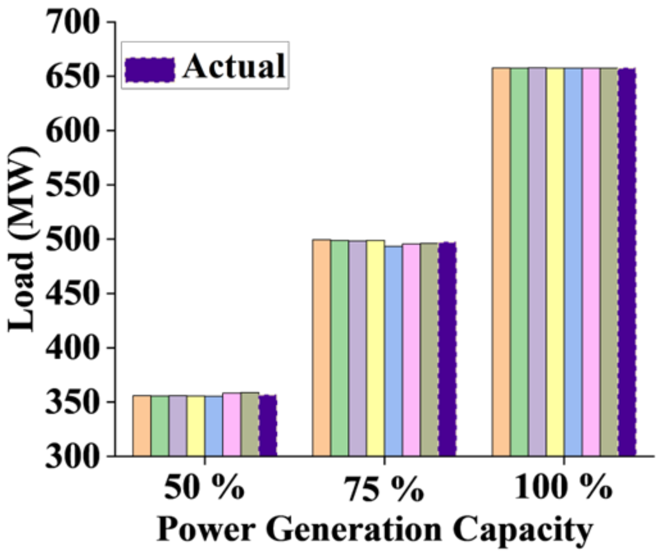

- The influence of the input variable(s) on the output variable is evaluated by the developed machine learning model



# Verification of the developed results

- The operational strategies to enhance the performance of the system corresponding to component, system and strategic level are tested on the power generation operation. A good agreement is found among the model-simulated and actual observations

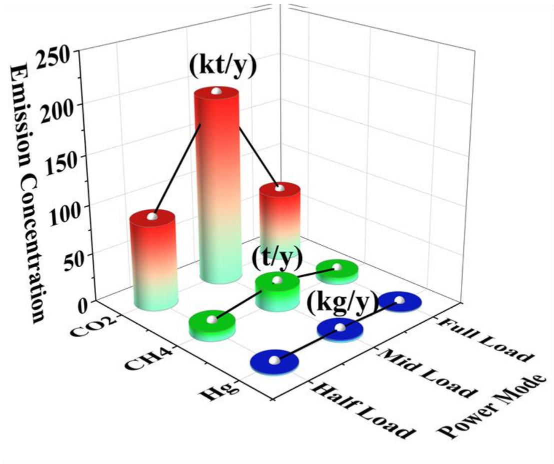


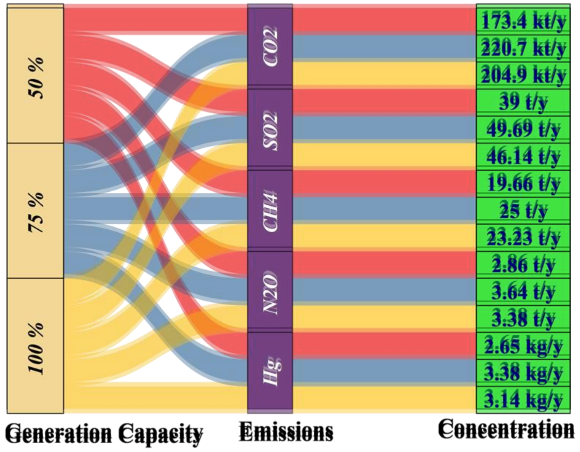



# Operational excellence of the power generation complex

- The operational excellence of the power generation system is achieved

| Generation | State | $\dot{m}_f$ (t/h) | Thermal Efficiency (%) | Heat Rate (kJ/kWh) |
|---|---|---|---|---|
| 50% | BAU | 138 | 39.41 | 9135 |
| | RSM-SV | 134 | 40.70 | 8846 |
| 75% | BAU | 195 | 38.97 | 9239 |
| | RSM-SV | 183 | 41.60 | 8653 |
| 100% | BAU | 241 | 41.89 | 8594 |
| | RSM-SV | 235 | 42.83 | 8406 |



# Conclusions

- Reliable and efficient utilization of data-driven machine learning analytics for performance enhancement of large industrial complexes is a potential opportunity. The analytics should be conducted considering the challenges in terms of data-processing and visualization, selection of relevant ML model, sensitivity analysis, experimental validation of the simulated results and extending the analytics for estimating the performance enhancement of industrial complex which are addressed in this work
- ML models like ANN, SVM and ELM are trained under rigorous hyper-parameters tuning. ANN may perform well for quantitative nature of problem (component, system), while SVM / ELM can better model problem of qualitative nature (strategic)

# Conclusions

- Variables significance analysis and extensive parametric study are conducted, and the results are supported by the domain knowledge of the power plant
- The ML model-simulated findings are validated on the real-operation of the power plant and significant savings in fuel consumption, improvement in energy efficiency and significant reduction in emissions (210.2 kt/y) are achieved [2,3]

[2] Ashraf, W. M., Uddin, G. M., Arafat, S. M., Krzywanski, J., and Xiaonan, W., 2021, "Strategic-level performance enhancement of a 660 MWe supercritical power plant and emissions reduction by AI approach," Energy Conversion and Management, 250, p. 114913
[3] Ashraf, W. M., Uddin, G. M., Ahmad, H. A., Jamil, M. A., Tariq, R., Shahzad, M. W., and Dua, V., 2022, "Artificial intelligence enabled efficient power generation and emissions reduction underpinning net-zero goal from the coal-based power plants," Energy Conversion and Management, 268, p. 116025.

# Future work

- The energy efficiency improvement and emissions reduction potential using machine learning enabled modelling and optimization of **fossil-based global energy assets** (coal, gas and oil), and quantifying the performance enhancement under uncertainty