Neural Networks for Predictive Control of SMRs in Industrial Energy Systems

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Introduction & Motivation

The decarbonization of energy-intensive industrial processes is one of the most urgent priorities in the global effort to mitigate climate change. In this context, small modular reactors (SMRs) are gaining increasing attention as promising sources of both electricity and process heat. Industrial deployment of SMRs, however, introduces a new operational challenge: the need to dynamically balance the production of electricity and heat, while simultaneously responding to the demands of modern power grids. These grids—characterized by high shares of intermittent renewables—require nuclear units to not only act as stable producers but also provide flexibility and even ancillary services, such as frequency regulation or load-following.

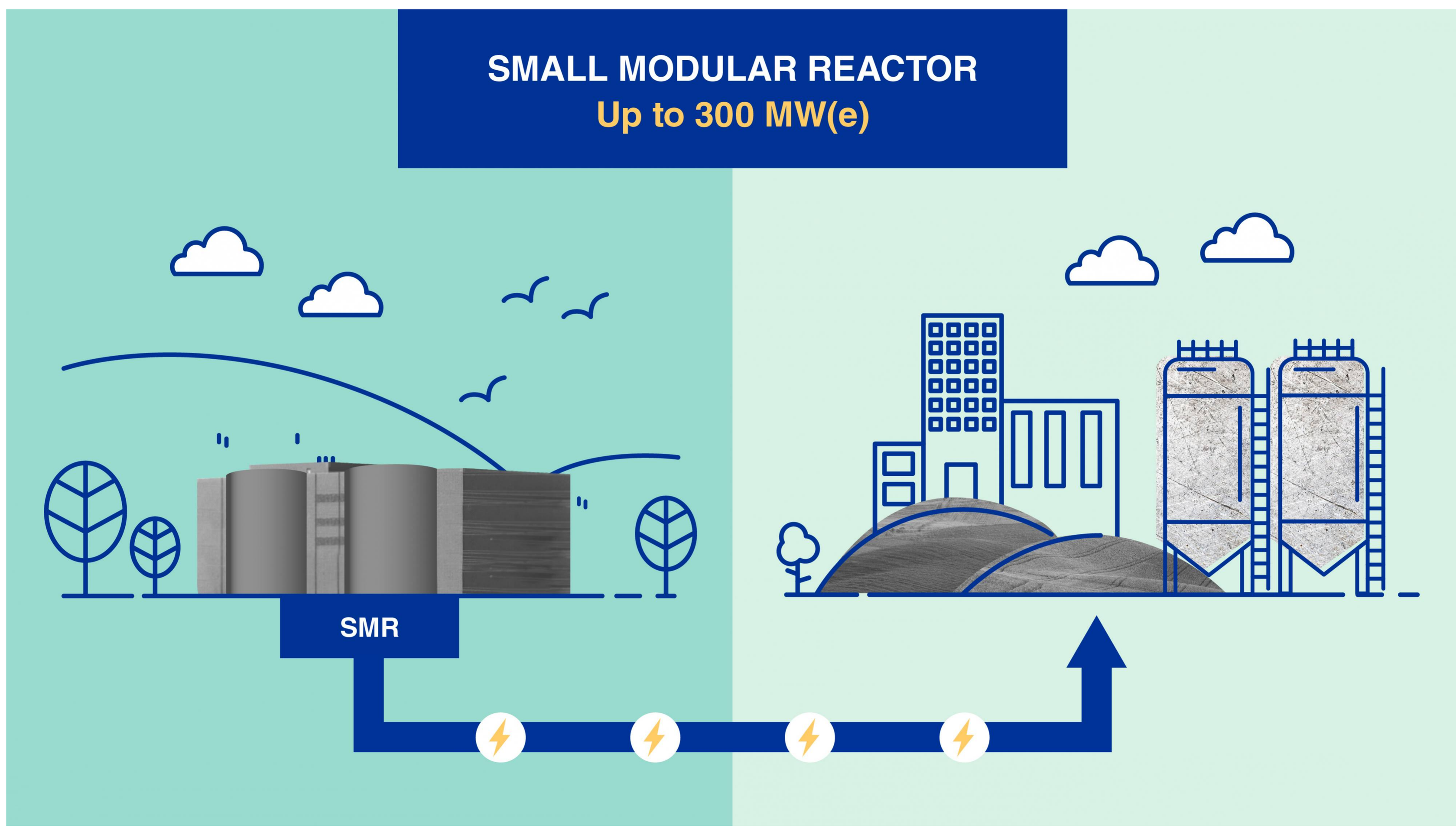

Figure 1. IAEA illustration: The use of nuclear power beyond generating electricity [1]

Objectives and Goals

Goal of this work: To present a neural-network-based predictive control framework for optimizing SMR operation in hybrid electricity and heat supply systems.

To achieve this, we focused on:

- Developing a **flexible methodology for neural network (NN) prediction and control,**
- Creating tools for **forecasting and optimizing SMR operation for heat and electricity,**
- Integrating **predictive control with real data and NNs.**

Flexible methodology for NN prediction and control

The deployment of NNs in energy systems requires more than just choosing the right architecture—it begins with building high-quality, validated datasets. In our work, we focused intensively on the methodology of dataset construction, ensuring that inputs to the models are accurate, reliable, and generalizable.

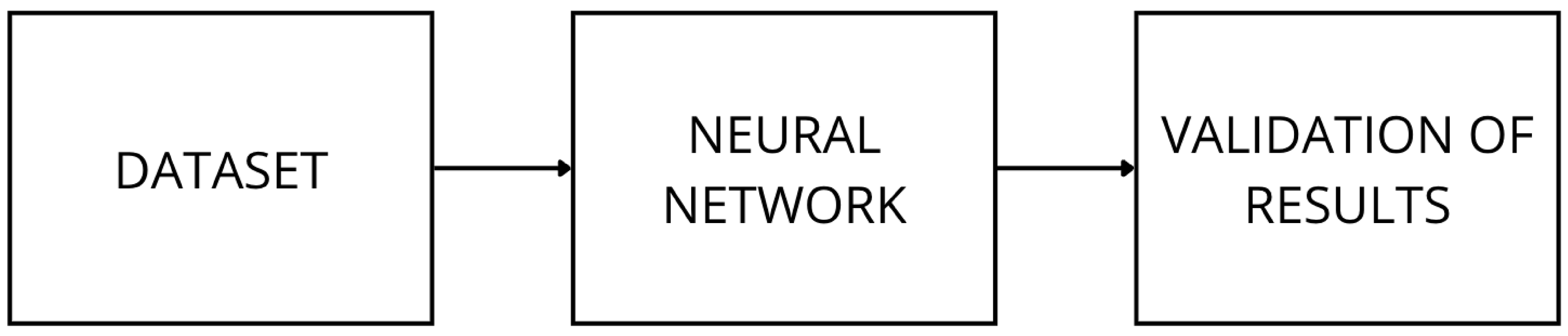

Figure 2. Methodology of the developed tools for the use of NNs

We have developed a comprehensive software framework for:

1. Data ingestion and preprocessing, integrating historical grid data (e.g., from Czech Transmission System Operator ČEPS), weather forecasts, and operational data,
2. Validation and verification tools, allowing automated quality control of time series inputs,
3. Modular implementation, enabling use across various sectors (nuclear, district heating, renewables integration).

Figure 3. Developed tools for dataset preparation, validation, and visualization

Once the data foundation is established, we employ advanced optimization techniques to fine-tune model performance. Specifically, we utilize the Optuna optimization framework to perform:

- Hyperparameter tuning of Recurrent Neural Networks (RNN) such as LSTM and GRU, as well as Transformer models,
- Multi-objective search to maximize forecasting accuracy and model generalizability,
- Efficient evaluation of large neural network configuration spaces using cross-validation and parallel computing.
- Feature Attention Mechanisms - highlight the contribution of each input variable, improving model transparency and supporting safe deployment in nuclear applications.

Forecasting and optimizing SMR operation for heat and electricity

SMRs offer a unique capability to serve both the electricity grid and industrial thermal loads. However, operating a nuclear system in such a dual-role introduces significant complexity. At any given moment, operators must decide how to split the reactor's thermal output between:

- Electricity production, which can be sold to the grid or used locally,
- Heat delivery, required by industrial processes, district heating, or cooling systems.

This dual-role operation creates a multi-objective optimization problem:

- Ensure reliable heat supply for industrial consumers,
- Maximize economic return via electricity sales or ancillary services,
- Respond to real-time grid signals and forecasts.

Achieving such coordination requires advanced control strategies that go far beyond traditional setpoint. It demands forecasting capability, fast adaptation, and the ability to learn complex dependencies between external variables (e.g., weather, market prices, industrial schedules).

Predictive Control with Real Data and NNs

We present a neural-network-based control framework for SMRs in hybrid electricity-heat systems. The toolset enables:

- Forecasting key variables (e.g., grid imbalance, weather effects, generation of NPPs - see Figure 4),
- Optimizing SMR dispatch for electricity and heat,
- Supporting ancillary services (aFRR, mFRR) and thermal storage management.

By anticipating system dynamics, the controller adjusts SMR output in advance—improving flexibility, reducing unit stress, and enhancing market participation.

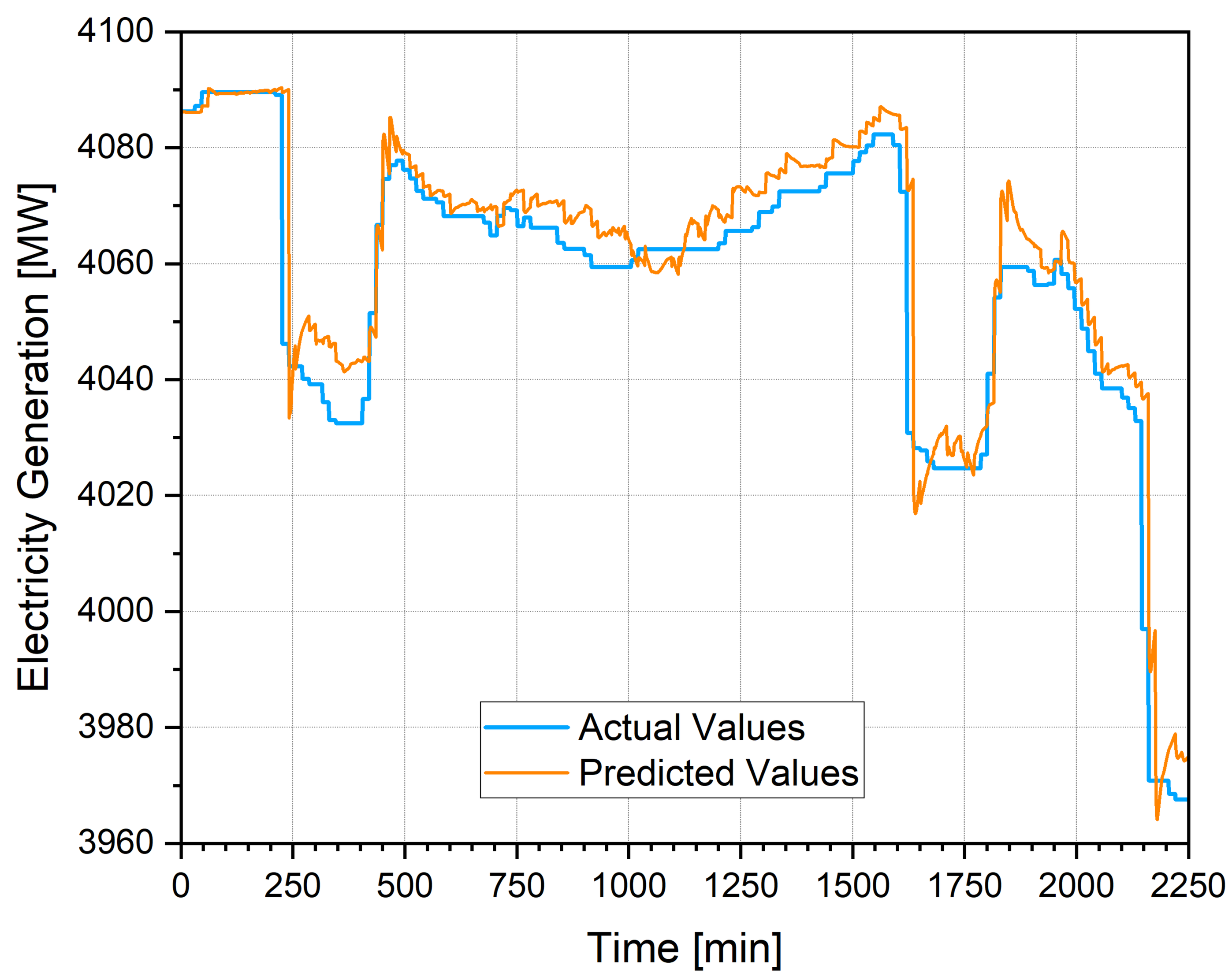

Figure 4. 15-minute ahead predictions of NPP generation in the Czech Republic [2].

Conclusion & Future Work

This work presents a novel methodology for integrating SMRs into hybrid energy systems by leveraging neural network-based predictive control. We developed a robust data infrastructure, including custom software tools for dataset validation, transformation, and neural network optimization using *Optuna*. These tools are designed to be flexible across multiple industrial sectors [3].

Our results demonstrate that accurate forecasting of electricity grid dynamics and thermal demand can significantly enhance the operational flexibility of SMRs.

Future work will focus on expanding predictive capabilities toward industrial heat demand modeling and techno-economic optimization under market scenarios, further increasing the applicability of intelligent SMR operation in real-world conditions. In collaboration with **industry partners**, we will continue efforts to implement our tools in real applications—both for **TSOs** and for **operating nuclear/thermal power plants**. Particular emphasis will be placed on deployment and testing of our predictive control framework in the **state of Texas (USA)**, where diverse market conditions and industrial clusters provide a valuable testbed for SMR integration.

References

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