NUCL-AI: Sustainable Electrification of Decentralised Regions through Nuclear Microreactors and AI-based Demand Predictions

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Abstract. This paper presents NUCL-AI, a novel approach that combines artificial intelligence (AI) with nuclear microreactor to enable sustainable electrification in remote and hard-to-reach regions. By leveraging AI's predictive capabilities, the proposed system predict energy demand in decentralised regions and uses transportable nuclear microreactos. A case study in Acre, Brazil, demonstrates the feasibility of deploying Westinghouse's eVinci microreactor, highlighting its potential to deliver reliable, low-cost energy with an estimated investment recovery period of just over eight years. Beyond environmental benefits, this model fosters economic development and infrastructure investment, contributing to a more equitable energy transition. NUCL-AI offers a scalable and resilient solution for accelerating decarbonisation and inclusive growth in underserved areas worldwide.

Keywords: Microreactor, Artificial Intelligence, Predictive model, Decentralised systems, eVinci, Electrification,

1 Introduction

Climate change is one of the greatest challenges facing planet Earth today. Combating climate change requires not only greater awareness of individual actions but also technological advancements by societies to prevent its causes and foster sustainable growth. One of the greatest challenges for sustainable development is the decarbonisation of energy resources and industrial processes. However, this progress must not be limited solely to the environmental sphere; it must also be economically viable. If decarbonisation is not economically sustainable, it will be very difficult to establish itself as the industrial norm.

2 Market need

Decentralised electricity grids are a promising option to support industrial decarbonisation, primarily because they leverage sustainable technologies such as renewable energy sources. Furthermore, decentralised grids also leverage local energy sources, resulting in reduced transportation costs and energy losses, making them an environmentally and economically sustainable concept. However, decentralised electricity grids must have strong internal connections to be efficient. This means that a poorly connected area can easily become isolated, deteriorating its economy and forcing it to use fossil fuels due to their low prices in an attempt to remain competitive. This problem is even more acute for remote areas poorly connected to traditional grids. This can be seen in the Spanish electricity grid, where the mainland grid is separated from the Canary Islands grid, and the mainland grid is only weakly connected to the autonomous cities and the Balearic Islands. In Spain, this weak internal connection forces poorly connected areas to use diesel engines for power generation. It can also be seen how these areas struggle to grow industrially because there is no energy backup for a potential increase in electricity demand. To combat climate change, it is essential that decarbonisation be a comprehensive concept that leaves no region behind. It can be seen how, with the traditional, decentralised concept of electricity grids, remote and poorly connected areas tend to be excluded and unable to advance at the same pace as the rest in their economic and environmental development. This lack of integration causes these regions to fall behind, hindering investment in the area and causing greater environmental damage, which in turn further deteriorates the local economy. To this end, an innovative concept has been proposed that combines nuclear energy and predictive artificial intelligence models to predict electricity demand in these areas and thus support them in their decarbonisation mission without compromising economic stability. In turn, these areas will become competitive thanks to their low energy prices, thus boosting their economic development. With economic development comes increased investment in the area, and with this, in the long term, an improvement in infrastructure, leading to improved grid connectivity and sustainable local energy production, generating greater economic growth and greater sustainable development for the region. This concept not only contributes to the fight against climate change but also promotes a model of equitable and sustainable growth, integrating all regions into the global energy transition. The following explains how the predictive model developed in this project works. For validation purposes, data from the Canary Islands were used due to data accessibility. A market study was then conducted to determine the project's application area, which was chosen as the Acre region (Brazil) due to its potential population growth.

3 Electrical demand prediction model

An artificial intelligence-based tool has been developed to predict energy demand in isolated areas or those with limited access to the electricity grid. To validate its operation, the Canary Islands was used as a case study, due to the availability of energy consumption data. The tool's operation and the results obtained are detailed below. The process begins with the loading of historical energy consumption data, which is then subjected to a cleansing process to eliminate irrelevant information. The data is divided into three groups: training, validation, and testing. Four years of data from the Canary Islands Statistics Institute database [1] were used to train the model. The validation phase uses 20% of the training data to ensure that the model neither underfits nor overfits the results. Finally, the test data set is used to evaluate the final performance of the model. The implemented model is N-BEATS (Neural Basis Expansion Analysis for interpretable Time Series forecasting) [2], a model developed by ElementAI to predict time series. This model is a hybrid between a neural network (NN) based model and statistical models, capable of quickly learning complex behaviors and explaining trends and seasonality, elements that can be lost or not interpreted by other NN models. In this case, 2 stacks are used (trend and seasonality) with 3 blocks each and 128 hidden layers per NN.

The windowing method of this model learns from the data given in the previous window and infers forecast results. The prediction is online, allowing for continuous model updates as new data are obtained, improving its accuracy over time. Several metrics are used to evaluate the model, although the most important are the Coefficient of Determination (R^2) and the Symmetric Mean Absolute Percentage Error (sMAPE). While R^2 better assesses the overall variability of the data, sMAPE works well for relative errors, normalizing them and not responding as much to extreme values.

$$R^2 = 1 - \frac{SS_{RES}}{SS_{TOT}} = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \overline{y}_i)^2} \tag{1}$$

$$\text{sMAPE} = \frac{100}{n} \sum_i^n \frac{|\hat{y}_i - y_i|}{(|\hat{y}_i| + |y_i|)/2} \tag{2}$$

Figures 2 and 3 show a diagram summarizing the process explained above and the results obtained for the electrical demand of the Canary Islands.

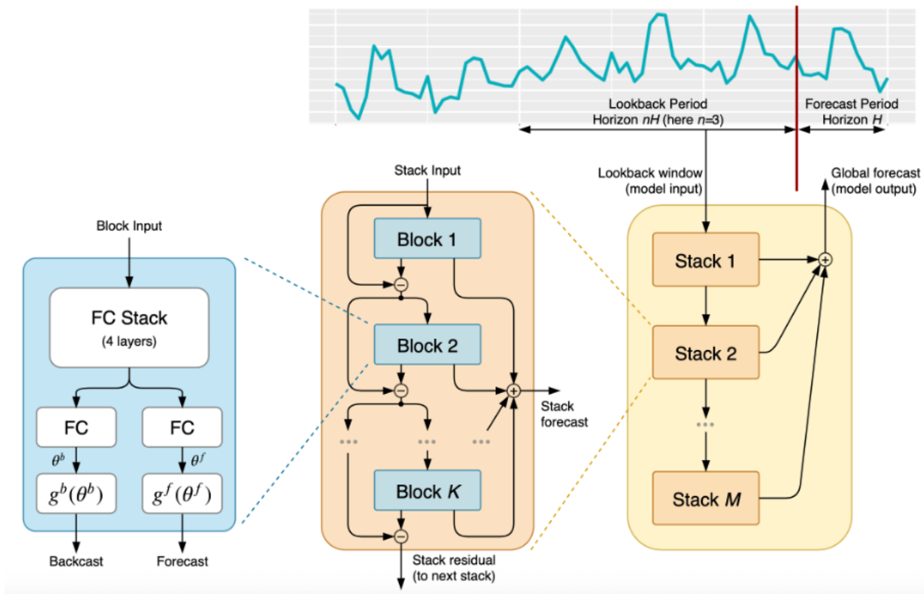
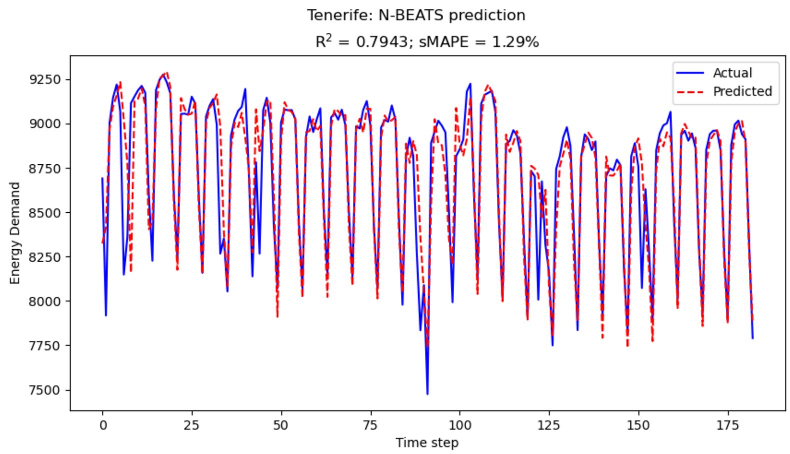


Fig. 1: Architecture of the N-BEATS model. It is based on connected NNs that predict in both temporal directions (forecast and backcast), such that each block learns past behaviors. Each stack is made up of K blocks, whose results update the parameters.

The ultimate goal of this tool is to optimize power supply management in isolated areas through the use of small modular reactors (SMRs) and portable microreactors. These technologies offer several advantages:

- Energy autonomy: SMRs and microreactors can operate independently without needing to be connected to the main grid.
- Reliability and stability: They provide a constant and predictable supply of power, ideal for areas with limited electrical infrastructure.
- Advanced safety: Designed with passive safety systems, they significantly reduce the risk of accidents.
- Installation flexibility: Their modular design allows them to be transported and installed in remote locations with relative ease.
- Low environmental impact: They generate low carbon emissions, contributing to energy sustainability.

This combination of intelligent demand forecasting and power generation using small-scale nuclear reactors facilitates the efficient and sustainable electrification of remote or hard-to-reach communities.



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4 Market and economic study

Market study

We have developed artificial intelligence capable of predicting electricity demand in different areas, and after analyzing several options, Acre (Brazil) stands out as an ideal candidate for implementing advanced energy solutions. Brazil was selected for this study for several key reasons. It is an emerging country and part of the BRICS, with constantly growing electricity demand and large swathes of naturally isolated territory, such as the Amazon. Furthermore, Brazil has a nuclear regulatory body and already has established nuclear infrastructure, which facilitates the implementation of new solutions in this area. Acre, in particular, is a region with very specific characteristics: it is semi-isolated from the rest of the country due to its Amazonian geography, which complicates its connection to the national electricity grid. Its population has been growing steadily (1% annually), exceeding 830,000 inhabitants in 2020 [3], with several urban centers of more than 20,000 people distributed along the same highway. The most populated cities, such as Rio Branco (387,852 inhabitants), Cruzeiro do Sul (98,382 inhabitants), Sena Madureira (43,916 inhabitants), and Tarauacá (46,517 inhabitants), are aligned along BR-364, a national highway that facilitates mobility between them and the distribution of energy infrastructure. However, Acre is also one of the poorest areas in Brazil, making the rising cost of electricity further impact its economic development and quality of life. The problem is that the current infrastructure is not up to these needs. Power generation in Acre relies heavily on diesel generators and solar panels, but the latter have limited performance due to climatic and geographic conditions. Furthermore, the price of electricity continues to rise, making the situation even more unsustainable. A solution such as a micronuclear reactor could guarantee a more stable and lower-cost electricity supply, directly benefiting the population and enabling more sustained economic development. Brazil, with its energy infrastructure expansion plans and established nuclear regulations, presents the ideal context for testing this technology. Thanks to our AI, we can anticipate the evolution of electricity demand in the region and optimize decision-making to ensure efficient implementation. Everything indicates that Acre not only needs a better energy solution, but also has the right context to receive it.

Economic study

This economic study analyzes the financial feasibility of using an eVinci microreactor in the Acre region of Brazil. The system incorporates artificial intelligence and is capable of predicting demand. energy of the different cities in the region, so the Westinghouse eVinci microreactor was selected for its ease of transport by road, its operational autonomy, and its ability to provide a reliable source of energy in remote areas, thanks to its availability factor greater than 0.99. The implementation of the eVinci system requires an initial investment of $100 million [4], which will cover the construction, installation, and commissioning costs of the reactor. Regarding the cost of electricity production, values vary between $0.14 and $0.41 per kW [5], so the average of $0.2 per kW, or $200 per MW, was taken. This results in a more competitive generation cost compared to the average of $350 [6] per MW in Brazil. The electricity consumption of the North subsystem in Brazil is 8,005 MW [7], of which Acre represents 4.18%, equivalent to an approximate consumption of 334.61 MW. To determine the return on investment, consider an eVinci reactor operating at a capacity of 5 MW continuously for one year (8,760 hours). In this period, the total energy generated would be, and the respective economic profit in one year:

$$\begin{gathered} 5 \text{ MW} \times 8760 \text{ hours} = 43.800 \text{ MWh}; \\ 43.800 \text{ MWh} \times 150 \frac{\$}{\text{hours}} = 6.570.000 \text{ MWh} \end{gathered} \tag{3}$$

Thus, the estimated time to break even the initial investment of 70 million dollars is:

$$\frac{70.000.000 \ \$}{6.570.000 \ \$/\text{year}} = 10.65 \text{ years} \tag{4}$$

This means that, under optimal operating and electricity sales conditions, the initial investment could be recovered in approximately 10 years and 8 months. Once the investment is recovered, the generated revenue would become net profit. If the annual revenue of $6.570.000 is maintained and operating costs are considered to be between 10% and 20% of this revenue, the annual net profit would be in the range of:

- Conservative scenario (20% of operating costs): \$5.25 million
- Optimistic scenario (10% of operating costs): \$5.91 million

The eVinci project is a viable and profitable alternative for generating electricity. With a lower production cost than the national average and a reasonable payback period, it could generate sustainable long-term profits and guarantee the financial stability of its operators.

5 Conclusion

The application of artificial intelligence in combination with modular nuclear reactors or microreactors offers an innovative and sustainable solution for the electrification of isolated areas with difficult grid access. The predictive capacity of the developed model makes it possible to optimize energy supply and guarantee a stable supply, reducing dependence on fossil fuels and promoting the decarbonization of these regions. The Acre, Brazil, case study demonstrates that implementing an eVinci microreactor can provide reliable energy at a lower cost, boosting economic development and infrastructure investment. With an estimated payback time of just over eight years, this model is economically viable and sustainable over the long term. This proposal not only addresses the need to reduce carbon emissions but also fosters equitable growth, ensuring that no region is left behind in the global energy transition.

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