Small Modular Reactors and Greenhouse Integration: A Sustainable Path to Carbon-Negative Heating and Electricity

University of Windsor

Anup Jwala Poudel[1], David S-K. Ting[1], Rupp Carriveau[1*], Mohammad Tohidi[2], Travis Pettigrew[2]

[1]Turbulence and Energy Laboratory, University of Windsor
[2]CEDIR Group, Canadian Nuclear Laboratories

TURBULENCE & ENERGY LAB

Problem Statement

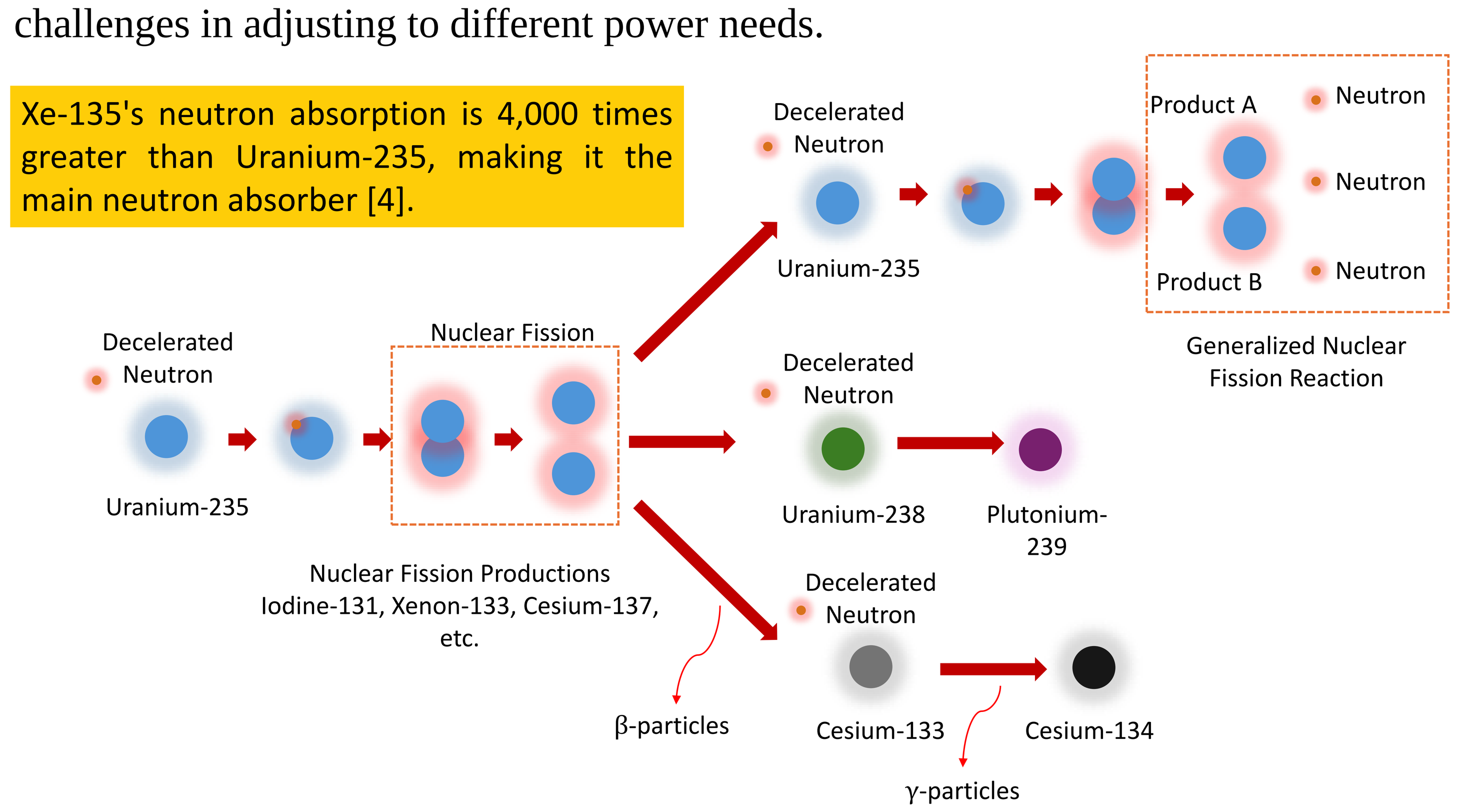
The increasing number of greenhouses has led to a growing energy demand to sustain agricultural yields. Greenhouse facilities typically require higher heating levels than indoor environments, resulting in significant fuel consumption. In Canada, heating greenhouses, necessary for about eight months of the year, is largely supplied by natural gas, which has the highest environmental impact and is a major contributor to greenhouse gas emissions [1]. While many greenhouses use passive or low-energy ventilation systems, electricity demand varies based on region, crop type, and scale. In Ontario, the Independent Electricity System Operator (IESO) projected a 180% increase in electricity usage in greenhouses between 2018 and 2024, particularly in the Kingsville-Leamington area [2]. Efforts have been made to provide heating and electricity through solar energy, still in northern regions like Canada, solar systems cannot fully meet demand due to winter inconsistencies in solar radiation [3].

Therefore, this study explores the potential of integrating nuclear energy, specifically Small Modular Reactors (SMRs), which are compact and well-suited for heating and electricity to greenhouses.

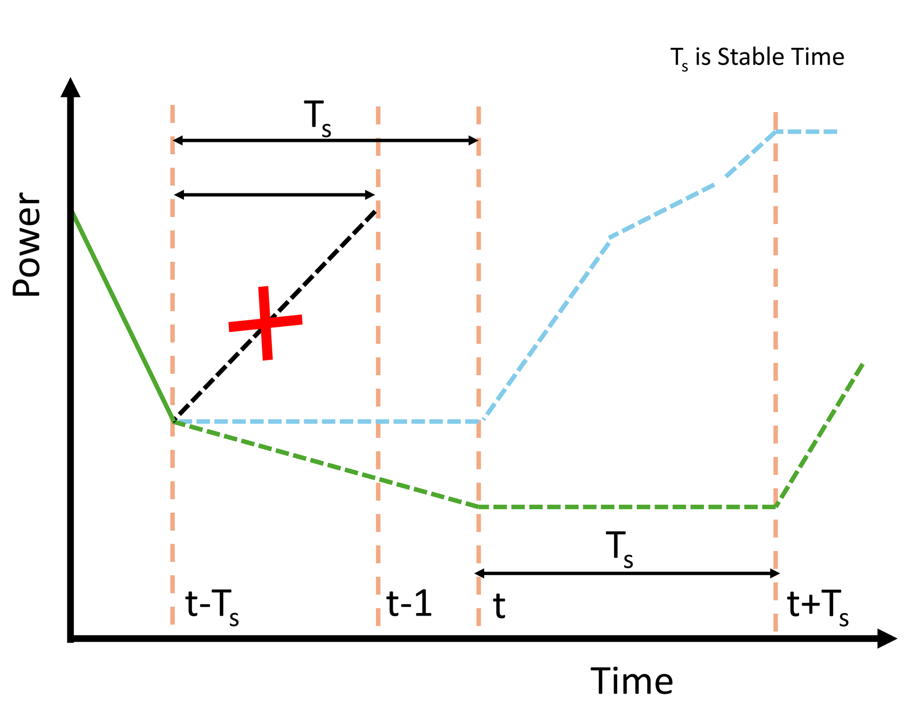
Background

SMRs are designed with load-following capabilities, however, during nuclear fission, a byproduct called Xenon (Xe) is produced. This buildup of Xenon, known as the Xenon effect, interferes with the reactor's ability to change its power output efficiently, creating challenges in adjusting to different power needs.

Xe-135's neutron absorption is 4,000 times greater than Uranium-235, making it the main neutron absorber [4].

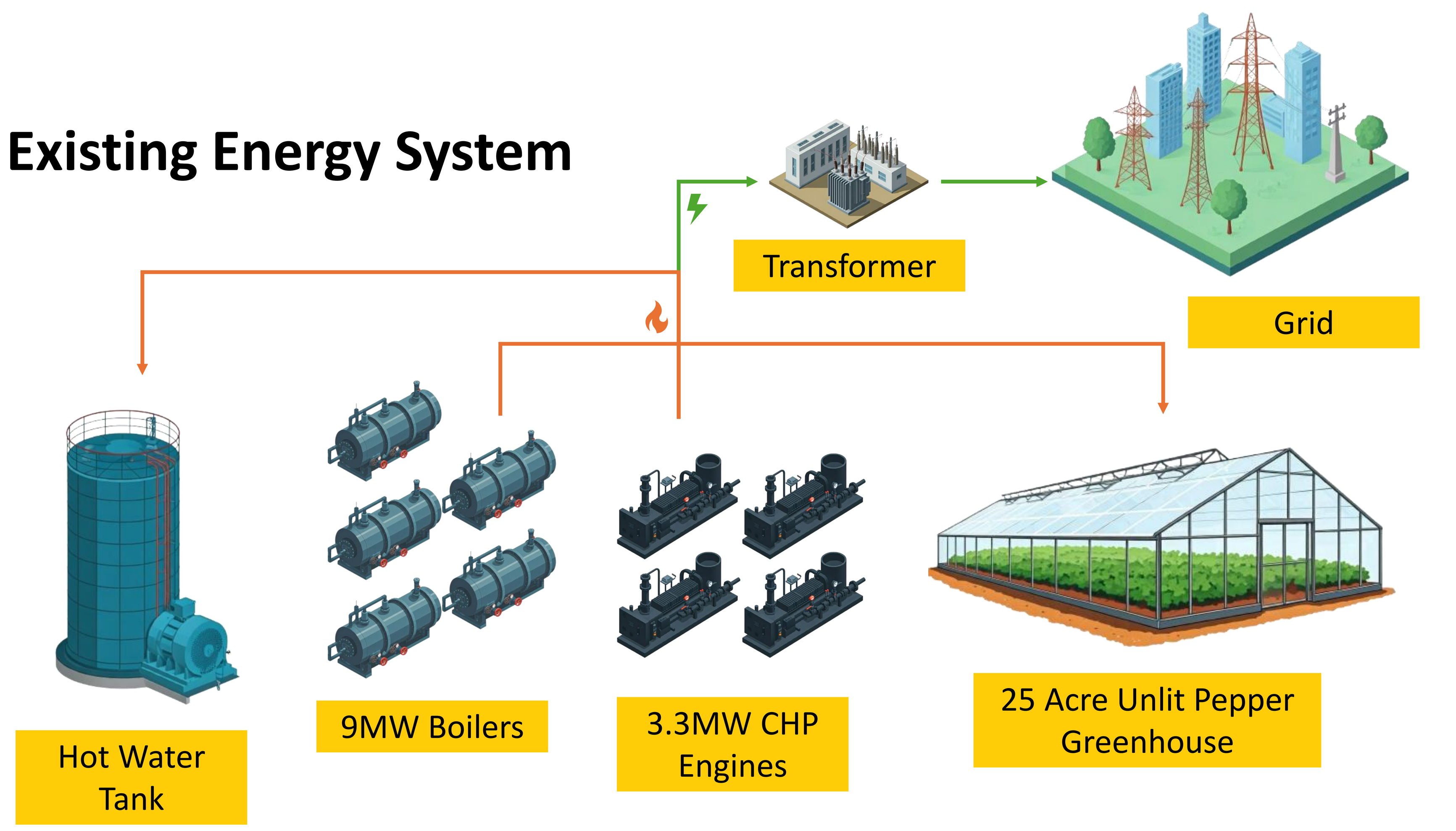


This graph shows output of SMR over time, specifically highlighting ramp-up and ramp-down behavior. At time $t - T_s$, there is a decrease in power output, followed by a restriction preventing any immediate ramp-up afterward. The red cross shows that a ramp-up is not allowed directly after the d ramp-down. Instead, SMR maintains a stable power level for T_s before further power adjustments can be made [5].

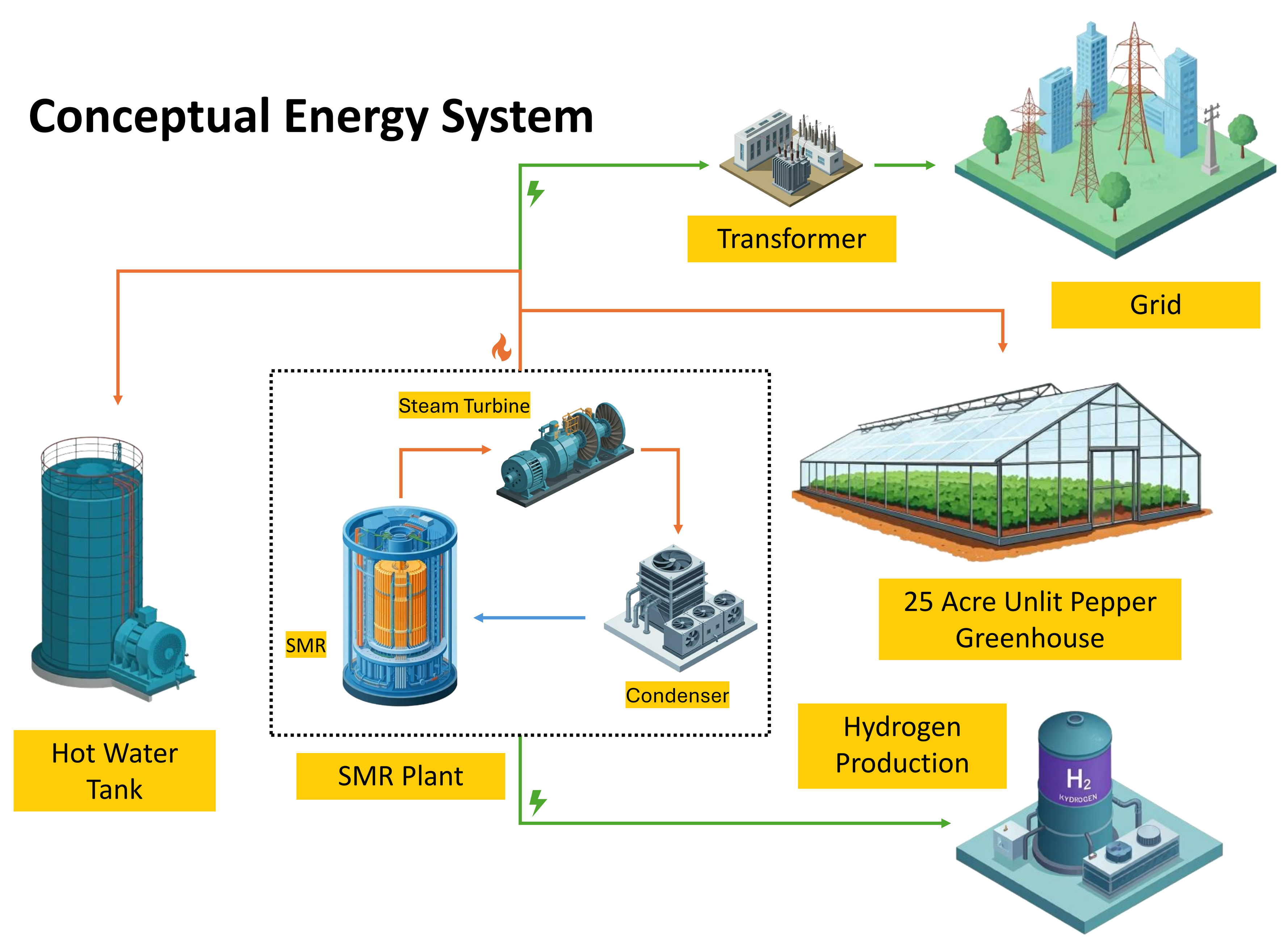


This operational limit of SMRs is known as the Xe-Poisoning. It causes SMRs to produce more power than required when attempting to follow load changes. In this study, the excess unused energy is quantified using a MATLAB model that simulates the output behavior of an SMR.

Existing Energy System



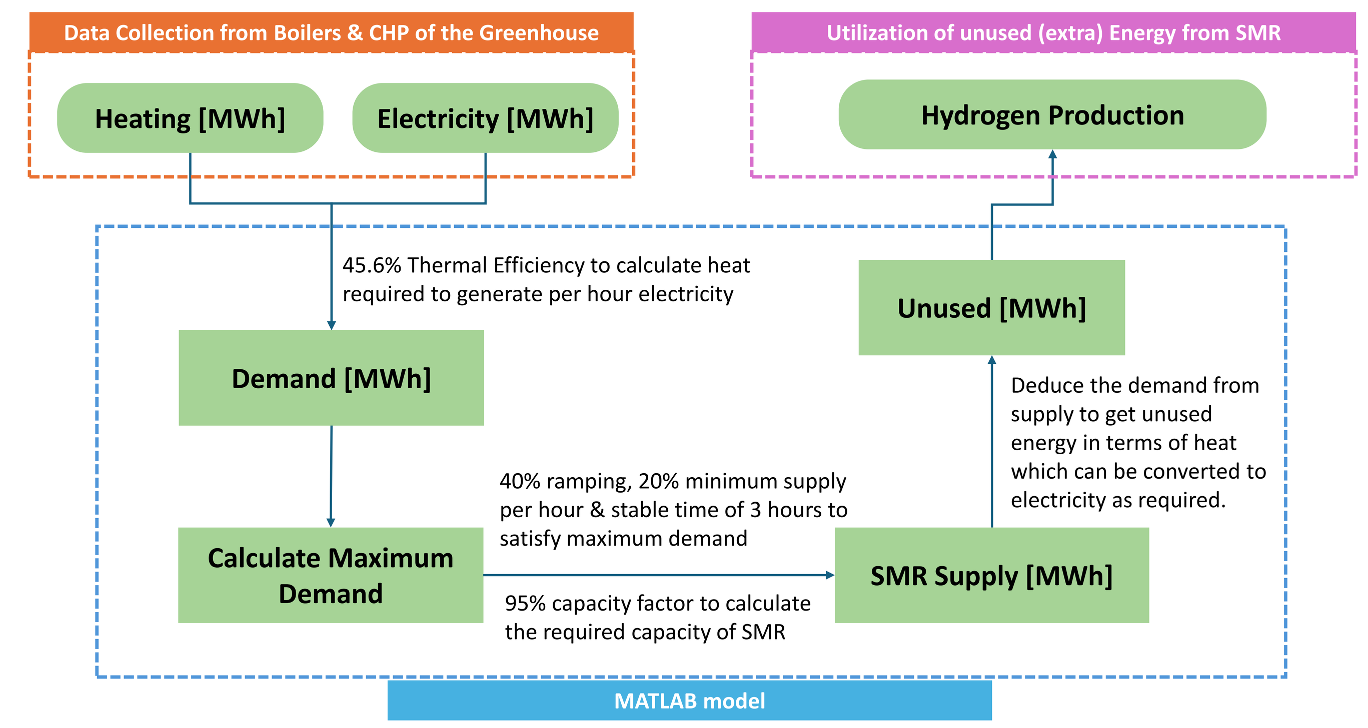
Conceptual Energy System

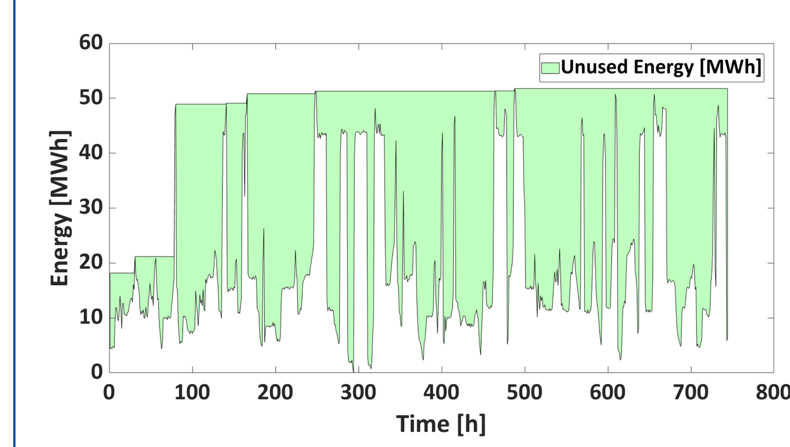


Energy System	Demand [MWh]	Supply [MWh]	Natural Gas Consumption [m^3]	Co_2 Emission [kg] [6]		Co_2 for 25 Acres Greenhouse [kg] [7]	Net Co_2 Emission [Tons]
				Without CCS	With CCS (η=90%)		
Existing (Boilers & CHP Engines)	86,794	86,794	8,960,000	16,128,000	1,612,800	2,102,400	**12,412.80**
Conceptual (SMR)	86,794	191,124	-	-		2,102,400	**-2,102.40**

Conceptual energy system needs approximately 2,100 tons of CO_2, while the existing system releases around 12,412 tons of CO_2, even when utilizing a Carbon Capture System (CCS) with 90% efficiency.

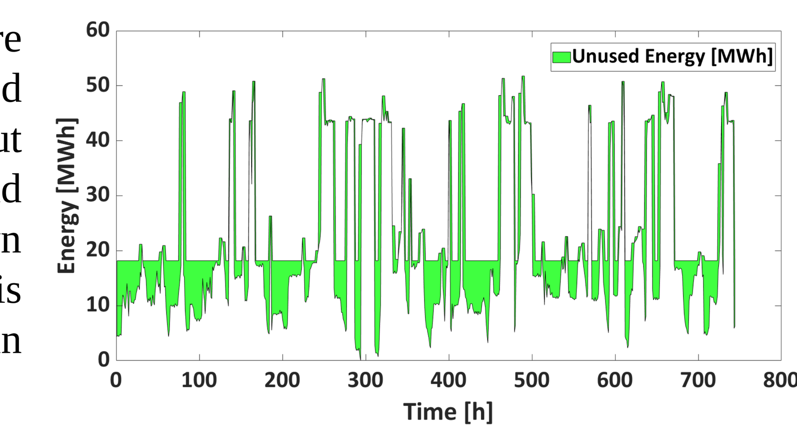
Discussion





In this study, we used hourly demand data from January 2022 to simulate the behavior of SMR. The simulation was conducted without providing future demand predictions to the model. Results indicate that the SMR maintains a stable output until the next anticipated peak in demand, ensuring that all energy requirements are met efficiently.

When the simulation included future demand values, the results demonstrated that the SMR maintained a stable output during designated stable periods and adjusted its output by ramping up or down according to demand fluctuations. This approach is more optimized, resulting in reduced unused energy.



The 2022 (entire year) simulation using greenhouse data showed 104,330 MWh of unused energy against a demand of 86,794 MWh. This highlights the need for future model optimization to minimize excess energy production.

Future Work

The model will be enhanced in future stages by efficiently capturing and using excess energy for hydrogen production. The integration is expected to improve sustainability and energy efficiency by converting surplus energy into a valuable resource. Additionally, a comparative and economic analysis will be conducted to understand the system's cost-effectiveness, and potential benefits. These efforts aim to provide essential insights for promoting clean energy practices within greenhouse operations.

University of Windsor
Greenhouse Technology Network
TURBULENCE & ENERGY LAB
Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

References

[1] M. S. Ahamed, H. Guo, and K. Tanino, "A quasi-steady state model for predicting the heating requirements of conventional greenhouses in cold regions," *Information Processing in Agriculture*, vol. 5, no. 1, pp. 33–46, Mar. 2018.

[2] IESO, "Greenhouse Energy Profile Study," Sep. 2019. Accessed: Apr. 09, 2024. [Online]. Available: https://www.ieso.ca/-/media/Files/IESO/Document-Library/research/Greenhouse-Energy-Profile-Study.pdf

[3] L. M. Semple, R. Carriveau, and D. S.-K. Ting, "Potential for large-scale solar collector system to offset carbon-based heating in the Ontario greenhouse sector," *International Journal of Sustainable Energy*, vol. 37, no. 4, pp. 378–392, Apr. 2018.

[4] Products in Nuclear Reactors [MOE], www.env.go.jp, Mar. 31, 2013 Accessed: Sept. 22, 2024. [Online]. Available: https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-02-03.html

[5] J. Rahman and J. Zhang, "Steady-state Modeling of Small Modular Reactors for Multi-timescale Power System Operations with Temporally Coupled Sub-models," IEEE Transactions on Power Systems, pp. 1–13, Jan. 2024

[6] Supplemental carbon dioxide in greenhouses," ontario.ca. Accessed: Sept. 22, 2024. [Online] Available: https://www.ontario.ca/page/supplemental-carbon-dioxide-greenhouses

[7] Process Ecology, "The thermodynamic cost of going 'green,'" Processecology.com, 2024. Accessed: Sept. 22, 2024. [Online]. Available: https://processecology.com/articles/industrial-energy-efficiency-and-carbon-capture-ccs-the-thermodynamic-cost-of-going-green

* Contact: rupp@uwindsor.ca