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Leveraging Data-Driven Techniques for Dynamic Modeling of a Solar Photovoltaic Thermal-Powered Carbon Capture System

Aina Aqilah Amran[a], Noor Fatina Emelin Nor Fadzil[a], Nor Syuriaty Jaafar[a], Ali Abbas[b], Norhuda Abdul Manaf[a,*]

[a]Department of Chemical and Environmental Engineering, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra 54100 Kuala Lumpur, Malaysia
[b]School of Chemical and Biomolecular Engineering, the University of Sydney, Sydney, NSW, Australia
norhuda.kl@utm.my

Global energy demand is rising rapidly due to population growth and accelerating industrialization. Integrating a post-combustion carbon capture (PCC) system into fossil fuel power plants has proven effective in reducing excessive CO_2 emissions. However, the addition of a PCC system introduces a significant energy penalty, negatively affecting overall power plant performance. To address this challenge, one promising solution is to couple the PCC system with renewable energy technologies, such as a solar photovoltaic thermal (PVT) system. This approach aims to offset the energy penalty by supplying the thermal energy required for the PCC reboiler and simultaneously generating electricity for the power grid. Nevertheless, the integration of a PVT–PCC system, as an emerging technology, exhibits dynamic and multifaceted behaviours, with many unknown parameters and complex process models. Present work aims to investigate the dynamic behaviour of the PVT–PCC plant by leveraging the nonlinear auto-regressive model with exogenous inputs (NLARX) technique to enhance simulation accuracy and system understanding. Based on the simulation analysis, integration of PVT with PCC via steam supply to the reboiler establishes a responsive thermal coupling that strongly governs the CO_2 capture and energy performance. Effective integration maximizes CO_2 capture efficiency and minimizes energy consumption when solar conditions and load profiles are properly matched, underscoring the potential of renewable-assisted carbon capture systems for sustainable emissions mitigation.

1. Introduction

Coal remains the largest contributor to CO_2 emissions within the energy sector, accounting for approximately 45 % of total emissions (IEA., 2024). Given this substantial contribution and the increasing electrification trend, it is imperative that nations prioritize the decarbonization of the power sector to meet global climate goals. A critical step toward achieving these targets involves retrofitting existing coal-fired power plants with carbon capture systems. Among the available carbon capture technologies, for instance pre-combustion, oxy-fuel combustion, and post-combustion capture (PCC), PCC is considered the most commercially viable option and features great potential for retrofitted options (Jin et al., 2019) particularly for coal power plants. However, PCC systems impose a significant thermal energy demand, primarily for solvent regeneration. Where, conventionally this thermal energy is extracted by bleeding steam from the power plant's steam cycle, which leads to a reduction in plant efficiency of approximately 10–40 % (Khalilpour et al., 2017). The additional energy demand often necessitates increased coal combustion to compensate for lost electricity output, introducing further CO_2 emissions during the process (Kumar and Tiwari, 2022). Integrating renewable energy sources particularly solar, has been demonstrated to partially or completely offset PCC reboiler duty. Where solar can directly supplement the reboiler at the desorber using steam to lower the intensive energy requirements. Extensive studies have been conducted on the integration of solar system (using thermal collectors) with PCC. According to the study, flue gas flow rate has a direct and significant effect on the CO_2 capture rate, although it has minimal impact on

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the performance of the solar collector system (Tang Zihan and Shen Jiong, 2025). Li et al., (2019) reported that the maximum energy efficiency generated from the solar assisted with PCC system ranges from 30-41 %. A prototype of a concentrating photovoltaic thermal (PVT) system, specifically designed for carbon capture applications, has been developed through a collaborative effort between two Norwegian companies (Emiliano Bellini, 2023). This innovative system is capable of harnessing both solar heat and electricity, with the goal of supporting decarbonization by supplying clean, renewable energy to carbon capture processes. The integration of this technology allows for the simultaneous generation of thermal and electrical energy. Thermal output is primarily directed to the reboiler in the PCC system and generated electricity can be used for the auxiliaries and/or send to the grid. Shen et al., (2022) have studied the parametric behaviour of adsorption-based carbon capture integrated with vacuum solar PVT collectors. They found that a larger PVT area yields more thermal and electricity output, although the quality of thermal energy is primarily influenced by the level of solar irradiance. In the integration mode, they also observed that the flue gas flowrate had a mild impact on the electricity generated by the PV panels. Despite its dual functionality, accurately predicting the dynamic performance of a hybrid PVT-PCC system under real-world conditions remains a significant challenge. This difficulty stems from the inherent variability of environmental factors, the complexity of the energy management, dynamic nature of PCC and photoelectric conversion process (Shen et al., 2022). Since the PVT-PCC system remains at a low technology readiness level, most researches has focused on the computational modelling rather than experimental studies. For instance, Nkurıyıngoma et al., (2021) used historical weather and PV power generation data to predict future energy output. The finding showed that a nonlinear autoregressive with exogenous inputs (NLARX) model can achieve high accuracy, outperforming traditional methods like feed-forward neural networks and statistical models. Building on this work, Pout et al., (2025) evaluated three different types of artificial intelligent based models for PVT systems. Among them, NLARX model exhibited the highest accuracy due to its ability to capture complex relationships between inputs and outputs. Jung et. al., (2023) applied NLARX model to embed with PCC control system. It was observed that the NLARX model demonstrated good agreement with the validation data assisting the development of an efficient control strategy for the PCC plant. Similar model performance was reported by Akino et al., (2019). Building on these promising results, , the present study aims to evaluate the performance of the integrated PVT-PCC system. By gaining insights into its dynamic behavior, this work seeks to support future industrial implementation and help pave the way for commercialization of the technology.

2. Data-driven system identification approach

2.1 PVT-NLARX model

Leveraging the power of real-time data set and data-driven model techniques as an artificial intelligence subset, the PVT model is developed by employing a multivariable NLARX technique. The experimental data was collected based on the actual PVT operation with the manipulation of solar irradiance (IR) from 200 to 1000 W/m² and inlet water flowrate to represent the dynamic condition. The PVT panel is fabricated using a commercial PV panel (maximum power at 50 W, monocrystalline silicon) and customized with thermal collector (copper tube diameter and length at 0.035 m and 1.3 m). The experiment was conducted using a solar simulator setup available at the Solar Energy Research Institute, National University of Malaysia (Figure 1(a)). The inputs of the model development are IR, inlet water flowrate, inlet water temperature, humidity, PVT surface temperature, and ambient temperature, while the outputs are outlet water flowrate, outlet water temperature, voltage, current, electrical and thermal efficiency. A total of 32544 input-output data were collected using multiple data logger systems. Data are segregated into two subsets, 70 % for model estimation and 30 % for model validation with the best-fit percentage as follows: outlet water flowrate (88 %), outlet water temperature (76 %), voltage (66 %), current (56 %), electrical (54 %) and thermal efficiency (70 %). After the validation process, the PVT-NLARX model with the best-fit percentage at one-step-ahead prediction output with 95 % confidence level is selected and exported to the Simulink® workspace with model structure as shown in Figure 1(b). To ensure the PVT panel (specifically thermal collector) can provide optimum thermal energy (hot water) to the reboiler system for solvent regeneration, an appropriate capacity scale-up is required.

2.2 PCC-NLARX model

This work adopts amine-based PCC model developed by Abdul Manaf et al. (2016). The simplified PCC-NLARX model, structured as a 4 × 2 system, was based on an actual pilot plant and is capable of capturing approximately 84.6 kg CO_2/h with a maximum capture efficiency of 94 % (Cousins et al., 2012). The main justification of employing the amine-based PCC plant model for integration with the PVT system lies in its technical maturity, its technology readiness level of 9 (Bukar and Asif, 2024) and the demonstrated reliability and robustness of the model under dynamic and integrated operating conditions (Akinola et al., 2019). The inputs are flue gas flowrate, CO_2 concentration in flue gas, lean solvent flowrate and reboiler heat duty while the

outputs are CO_2 capture percentage (CC) and energy performance (EP). For detailed model development and validation, one can refer to Abdul Manaf et al. (2016).

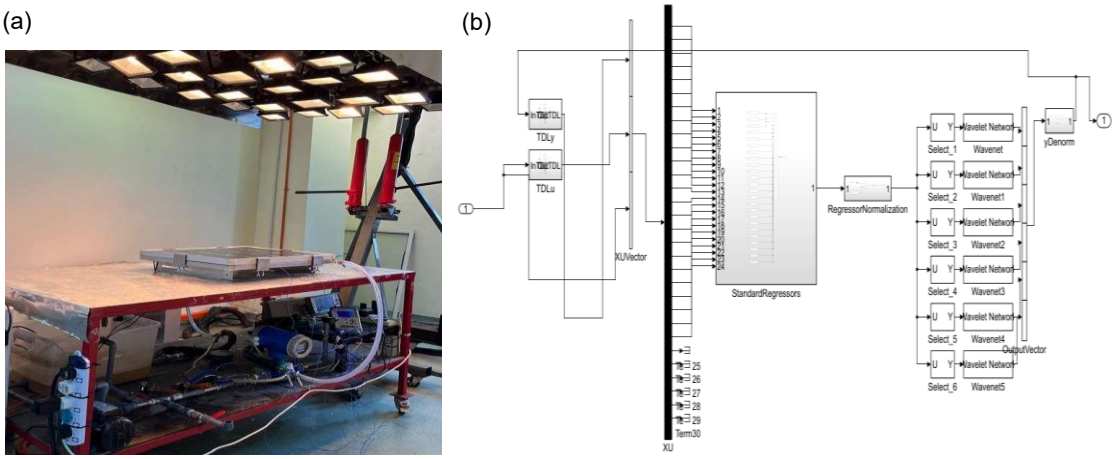

Figure 1: (a) An experimental setup of PVT system, (b) A PVT-NLARX model architecture

2.3 PVT-PCC-NLARX model

The regeneration temperature for amine-based PCC plant is between 110-120 °C (Khalilpour et al., 2017). In this condition, solar thermal energy serves as a promising heat source for solvent regeneration/reboiler duty without requiring any modification to the existing PCC unit operation (Wang et al., 2021). To ensure that the thermal energy generated from the fabricated PVT panel can accommodate the reboiler energy demand, an appropriate model scale up is required. Based on the PCC pilot scale capacity (94 % capture efficiency at~ 84.6 kg CO_2/h) a solar PVT system with an electrical capacity of 500 W complemented by matched thermal output, can fulfil most of the reboiler's energy requirements. This configuration can be imitated as a concentrated PVT (CPVT) system aligns with literature findings. For instance, CPVT achieves solar to thermal efficiency of 45 – 70 % (Mortadi et al.,, 2024) with a maximum operating temperature of up to 250°C (Lamnatou et al.,., 2021). In this work, the steam goes into the reboiler and provides the required energy for solvent regeneration, while the electric power produced by the PV cells is supplied directly to the grid for simplification as illustrated in schematic diagram in Figure 2(a).

The critical step in developing an integrated PVT-PCC model within the Simulink® environment involves exporting the NLARX system identification functions from MATLAB into Simulink® blocks. To avoid the computational complexity associated with MATLAB programming and nonlinear differential equations, a Nonlinear ARX model block was implemented to represent the data-driven NLARX models. While a Gain toolbox available in the Simulink® library is employed to demonstrate the PVT scale-up. The individual systems (PVT and PCC models) are integrated as illustrated in Figure 2(a), where the coupling interface connects the thermal efficiency output (η_{th}) from the PVT system to the reboiler heat duty (Q_R) input of the PCC system. This integration pathway is mathematically described by Eq(1), which establishes the functional relationship between PVT efficiency and the carbon capture system's reboiler energy requirements. This work leverages the established capabilities of NLARX models within the MATLAB/Simulink® framework, which enables the integration of nonlinear dynamic systems through standardized model interfaces and their capability to incorporate previous output feedback into the nonlinear model architecture (Li and Zhang, 2024).

3. Dynamic analysis of PVT-PCC system

The dynamic performance of the PVT-PCC system was analyzed based on temporal variations in input parameters, specifically IR, PVT surface temperature, and flue gas flow rate as illustrated in Figure 3(a). These inputs were evaluated for their corresponding effects on key system outputs, namely CC and EP. The transient trend of solar irradiance reflects the inherent intermittency of solar energy, which directly influences the surface temperature of the PVT system. Meanwhile, fluctuations in flue gas flow rate represent peak and off-peak operating periods of the coal-fired power plant, as defined within the study's boundary conditions (Figure 2(b)). These two parameters were selected due to the operational challenges they pose to the integrated system (Tang Z. and Shen J, 2025).Three different scenarios to represent the actual operation of PVT-PCC system is delineated in Table 1. In scenario 3, the thermal storage is implicitly assumed to be available to maintain the level of solar irradiance through the simulation period.

(a) (b)

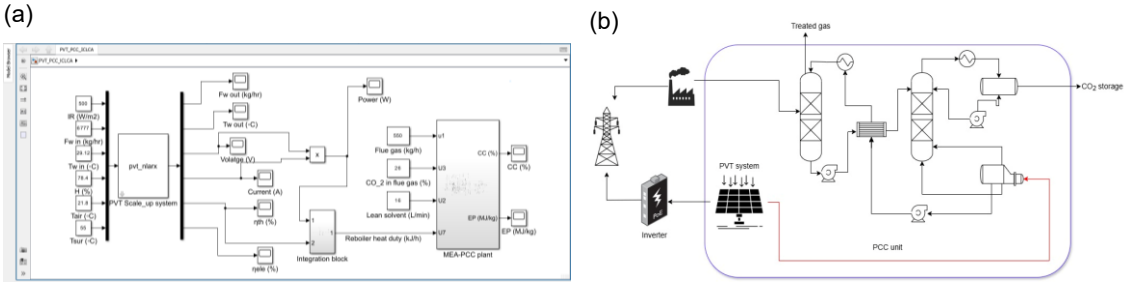

Figure 2: (a) A PVT-PCC-NLARX model in Simulink Mathlab environment (input data used at nominal operating condition, (b) A simplified schematic diagram of PVT-PCC plant (in pilot scale set-up)

$$Q_R = P_S * \eta_{th} * 3600 \quad (1)$$

Table 1: Three scenarios based on different input variations

Scenario	IR	PVT surface temperature	Flue gas flowrate	Heat storage
1	√	√	√	X
2	√	√	X	X
3	X	X	√	√

Figure 3(b) shows the performance of CC and EP for PVT-PCC plant under Scenario 1. It was observed that the CC improves markedly during the high irradiance periods, rising from ~50 % to peaks around ~90 %. This improvement is attributed to the increased reboiler steam availability, which promotes continuous and efficient solvent regeneration (Shen et al., 2023) , maintaining a high solvent absorption capacity. The EP improves significantly (with values dropping from 14 MJ/kg CO_2 in the morning to as low as 7 MJ/kg CO_2 around midday), reflecting the reduced parasitic energy load due to effective thermal integration. When solar irradiance is relatively low, the thermal output is insufficient to meet the full reboiler demand. This results in suboptimal solvent regeneration, causing a reduction in CC (~40–50 %) and a rise in EP values (10–14 MJ/kg CO_2), indicating higher specific energy consumption per unit of CO_2 captured. The effect is particularly evident when high flue gas flowrates are maintained without proportional thermal support, creating an energy mismatch at the PCC unit due to imperfect energy balance (Shen et al., 2023).

Figure 3(c) presents the dynamic response of PVT-PCC system under Scenario 2. During early morning,both IR and surface temperature remain relatively low, limiting steam generation and impairing solvent regeneration. This condition results in erratic and reduced CC (<50 %) and poor EP values spiking intermittently between 10–14 MJ/kg CO_2 due to unstable thermal supply-demand matching. From 12–2 PM, despite high IR and elevated PVT temperatures (~70 °C), the CO_2 capture efficiency remains low, which can be attributed to the constant flue gas flowrate. This leads to a thermal mismatch, as the steam supply from the PVT collector becomes insufficient relative to the increased reboiler demand. Consequently, solvent regeneration is compromised, resulting in reduced capture performance and persistently high EP values. A similar observation was reported by Alzhrani et al., (2023) where a significant amount of water introduced with the flue gas diluted the amine solution, reducing effective CO_2 absorption.

Figure 3(d) illustrates the performance of PVT-PCC system under Scenario 3. During the early hours, the thermal load from the flue gas is relatively low and can be adequately supported by the available steam. As a result, high CC (~90–100 %) and favorable EP (<6 MJ/kg CO_2) are observed. However, once the flue gas flowrate increases, a mismatch arises between the steam supply (limited by the constant irradiance) and the increased reboiler duty. This mismatch results in a noticeable degradation in capture performance, with CC dropping below 50 % and EP exceeding 10 MJ/kg CO_2, indicating inefficient regeneration and elevated energy consumption. After 2 PM, as the flue gas flowrate is reduced, the previously limited steam supply once again becomes sufficient relative to the lower thermal demand. This realignment enables a sharp recovery in CO_2 capture efficiency to ~100 % and a significant reduction in energy consumption (EP < 5 MJ/kg CO_2), reflecting optimized reboiler operation under steady thermal input and reduced load.

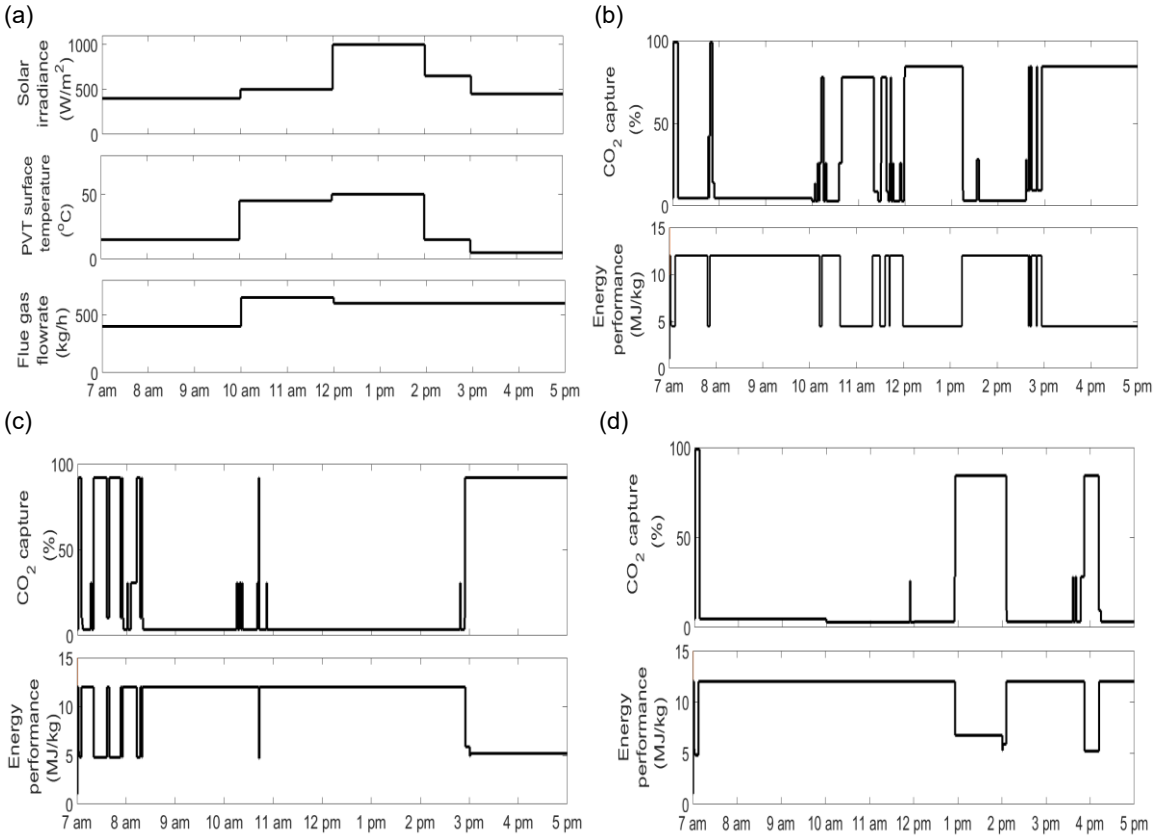

Figure 3: (a) Dynamic input pattern for IR, PVT surface temperature and flue gas flowrate (b) Dynamic response of PVT-PCC plant based on Scenario 1 (variation in solar irradiation, PVT surface temperature and flue gas flowrate) (c) Scenario 2 (variation in solar irradiation, PVT surface temperature) (d) Scenario 3 (variation in flue gas flowrate)

4. Conclusions

An effective operation of PVT-PCC system relies on synchronising solar-driven thermal availability with process load (solar irradiance and flue gas volume) system. Thermal undersupply during peak flue gas periods or thermal oversupply during low flow periods leads to inefficiencies in both CO_2 capture and energy performance. While the study successfully demonstrates a prototype under simulated conditions, challenges associated with real-world scalability remain unaddressed. These include the dynamic nature of energy management, high capital costs related to system installation, solar tracking, and maintenance requirements. To improve the system's applicability at scale, enhanced data acquisition particularly of dynamic operating parameters, is essential to increase model accuracy and output sensitivity (e.g., voltage and current), especially given the current lower best-fit performance. A robust economic evaluation is also necessary to assess lifecycle costs, return on investment, and competitiveness with existing CO_2 capture technologies. Addressing these scalability, technical, and economic challenges is critical for the real-world implementation and commercialization of the proposed PVT-PCC system.

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