Digital Twin-Enabled Hybrid HVAC Control for Enhanced Energy Efficiency – HESTIA concept

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***Abstract*—The decarbonization of the buildings' sector implies advanced control strategies for the heating, ventilation, and air-conditioning systems, as well as combining conventional and renewable energy technologies. This paper presents the conceptual foundations for implementing a digital twin–enabled control architecture for a hybrid HVAC system integrating a methane-fueled boiler and an air-source heat pump. The approach integrates physics-based models, an experimental-scale infrastructure with real-time data acquisition with predictive optimization techniques to enable energy-efficient system operation. A modular digital twin architecture is currently under development, providing capabilities for real-time state estimation, predictive simulation, and informed decision-making under dynamic weather conditions, tariff structures, and energy demand profiles. The proposed framework is scalable and applicable to smart buildings and different energy communities, bridging the transition toward intelligent, reliable and sustainable energy systems.**

Keywords—digital twin, hybrid HVAC system, predictive control, smart buildings.

I. INTRODUCTION

Given its rapid growth and significant energy dependence, the building stock requires integrated and clearly elaborated strategies to achieve targeted efficiency and, implicitly, decarbonization levels. For this, an Industry 4.0 technology – digital twin (DT) - has emerged and is widely seen as a key tool for advanced monitoring, control, and optimization of building energy systems. As generally defined by Lu et al. [1], a DT is a digital replica of a real, physical system, enabling the possibility of more complex analysis. Unlike conventional simulation models, digital twins assures continuous synchronization between the physical system and its virtual counterpart. Besides avoiding the classic methods' shortcoming, this approach allows real-time state and fault estimations, predictive analysis, and closed-loop control [2].

When dealing with climatization systems, DTs emerged as virtual replicas combining real-time data, high-fidelity physical models, and Artificial Intelligence (AI) algorithms to support, control and performance diagnosis. A new approach in terms of HVAC functionality is to merge two or more (sub)systems to increase the overall efficiency. In this regard, coupling an air-to-water heat pump (AWHP) with a methane gas boiler is a method increasingly adopted as a retrofit pathway to buildings' decarbonization. This approach allows exploiting the high energy performances of AWHPs at moderate temperatures besides using the gas boilers to maintain the desired interior comfort for peak loads or extreme outdoor condition. To assure a proper and efficient functionality, an automatization, or better a DT, is required to be implemented, while primary energy saving between 5 and 22% were found for different configurations and strategies [2], [3]. DTs can support the transformation of conventional building systems into adaptive, data-driven assets, though challenges such as data harmonization, model integration, and scalability remain [4]. A recent analysis paper gives prominence to the fact that advanced control strategies are vital to assure energy usage flexibility by anticipating future conditions and actions and companies already began integrating Model Predictive Control (MPC) in their products, reducing the peak power consumption with up to 65% [5].

There are many DT applications in buildings energy management [6]. They range from pure real-time monitoring, predictive maintenance to most complex data-driven self-optimization of energy consumption and enhanced occupants' comfort using AI algorithms [6], [7], [8]. Additionally, DTs can be used to implement self-adaptive control of hybrid multi-input HVAC systems, where virtual controllers are continuously fine-tuned using deep reinforcement learning algorithms which tracks a physical controller, enabling model-free adaptation without explicit system identification [9]. For heat pumps, a high-fidelity DT of an air-source enhanced by a fuzzy clustering and stacked broad learning system achieved very low prediction errors for COP in term of: MAE – 0.045, mean absolute percentage error MAPE – 0.012, and RMSE – 0.252, highlighting the importance of using AI algorithm in accurate estimations [10].

Although this quick literature survey showed no important study of fully developed DT of a residential hybrid gas boiler – AWHP hybrid system, several research papers which analyze some components or methods have been identified:

- component/system models: quasi-physical models of AWHPs and condensing gas boilers, validated at component level, enable detailed hybrid system simulation and studies of main parameters and overall efficiency: [2], [11].
- dynamic, integrated models: multi-zone simulations in TRNSYS, IDA-ICE, and Python-based frameworks couple building's thermal dynamics with hybrid generator models to study sizing and control: [2], [12], [13].
- data-driven and ANN-based controllers: ANNs trained on daily optimizations for hybrid AWHP–boiler–PV–battery systems can reproduce optimal solutions in real time without the need of a priori explicit forecasts [14].

This emphasizes the research gaps in the integration of DTs with hybrid HVAC systems. Moreover, limited attention has been given to residential hybrid heating systems in regions where natural gas wall-mounted boilers are predominant, such as Romania, where are installed more than 2.5 million units [15]. In this context, hybrid systems combining existing gas boilers with new air-source heat pumps represent an efficient way to reduce fossil fuel dependency.

In the given context, this paper proposes the concept of developing a DT of a test hybrid HVAC system composed of an integrated AWHP and a 20 kW natural gas boiler. The experimental infrastructure was recently mounted in Energy Faculty, POLITEHNICA Bucharest University, Romania.

Unlike existing studies that primarily focus either on isolated component modeling, static hybrid HVAC simulations, or purely data-driven prediction frameworks, the proposed framework particularly addresses retrofit-oriented hybridization of existing gas-boiler-dominated residential infrastructures, a configuration insufficiently investigated in current digital twin literature, especially within Eastern European building stocks.

II. THE PHYSICAL TWIN

The experimental infrastructure was developed through a research grant funded by national (Romanian) Ministry of Research, Innovation and Digitization. The HESTIA (Hybrid Energy System with Digital Twin Augmentation – website available at: https://hestia.upb.ro) research project aims at developing an experimental testbed for the systematic analysis of a hybrid heating and cooling system, whose operation is optimized via a digitally instantiated counterpart employing detailed dynamic modeling. Moreover, it will allow experimental validation of the potential of digital twin–enabled control to reduce fossil fuel consumption in existing buildings. The experimental platform comprises an air-source heat pump, a natural gas boiler, a photovoltaic (PV) generation system, a thermal energy storage unit (boiler tank), and high-performance data acquisition and monitoring infrastructure. A digital twin of the physical setup is currently in development and will support real-time control, performance evaluation, and virtual experimentation.

A key objective of the HESTIA project is to identify and evaluate optimal operational and control strategies for the integrated subsystems, aiming at minimizing the natural gas consumption and grid electricity demand, while maximizing the utilization of PV-sourced electrical energy to drive the heat pump. Finally, the project initiates at a technological readiness level corresponding to TRL 2 and, through iterative experimental investigation and validation under controlled conditions, targets advancement to TRL 4.

Currently, the stand is assembled, but the experimental campaign has not yet been carried out since the monitoring system has not yet been added, but the optimal solution to measure the parameters of interest has been identified. The experimental infrastructure (shown in Fig. 1) is, mainly, composed of:

- an 8kW monoblock heat pump (R290 refrigerant)
- a 20kW condensing methane gas boiler
- a 150liter hot water tank
- a 40liter buffer boiler
- ambiental thermostat
- specific mounting accessories

Fig. 1. The physical twin – the hybrid HVAC system

The heat pump is equipped with a 3kW internal single-phase electric resistance, which can be parametrized depending on the external temperature, difference in the thermal water inlet and outlet temperature, working time periods, etc.

The system is connected to the PV system mounted on the building's roof, with an estimated output power of 66 kW.

This configuration was chosen based on the fact that natural gas boilers are the most common heating system in Romania together with district heating. Moreover, this configuration allows the simple addition of the AWHP (and optionally the hot water tank) to the existing system, thus decreasing the environmental impact of existing building through the retrofit process. Moreover, the HP was chosen based on its performances and the working fluid. The R290 refrigerant (propane) has a very lor estimated Global Warming Potential (3), compared with other commercial refrigerants. Additionally, compared with R32 – a synthetic refrigerant – the propane has zero Ozone Layer Deletion Potential, present better the thermodynamics properties, thus superior energy efficiency rations (could reach A+++ energy efficiency labels). However, one shortcoming is represented that, being a hydrocarbon, is more flammable (class A3) compared with synthetic working fluids. But the fact that the AWHP is a compact closed system, the fire hazard is relatively low.

In addition to the experimental testbed, the HESTIA project will develop a digital twin–enabled cyber-physical framework that represents a virtual counterpart of the physical hybrid HVAC system and will be continuously updated using real-time measurement data. This approach supports the digitalization and control-oriented integration of hybrid HVAC systems, contributing to the limited body of existing work on digital hybrid energy systems. The digital twin will enable advanced monitoring, dynamic system modeling, automated fault detection and diagnosis, and energy consumption forecasting, while supporting decision-making and optimal control strategies aimed at minimizing natural gas consumption under time-varying energy pricing constraints. Moreover, this modular framework will allow virtual scenario analysis to evaluate alternative operational strategies and assess the performance of different equipment configurations.

III. THE DIGITAL TWIN

The HESTIA DT will incorporate a three-dimensional representation of the physical hybrid HVAC system, including ducts, vents, pumps, piping, and associated components, accurately reflecting their spatial configuration within the real installation. This 3D interface will be continuously synchronized with sensor data acquired through the data acquisition infrastructure, with system interoperability ensured via a SCADA-based communication architecture. Beyond visualization, the digital twin will enable dynamic analysis of system's behavior under varying operating regimes, control strategies, and external conditions through detailed mathematical modeling. It will integrate control and decision-making algorithms for optimal HVAC operation considering temperature setpoints, occupancy schedules, thermal loads, available energy resources, and dynamic energy pricing. These functionalities will be supported by AI-based models, including artificial neural networks, to enable advanced capabilities such as predictive control, performance monitoring, and automated fault detection.

The overall HESTIA Model and Decision computational core comprises three physics-informed predictive sub-models for each main component. Thus:

A. Air-Source Heat Pump — Physics-Informed Neural Network

A purely data-driven model is inadequate for ASHP performance prediction due to poor extrapolation outside the training distribution across the wide Bucharest ambient temperature range (−12 °C to +43 °C). A grey-box Physics-Informed Neural Network (PINN) is therefore adopted, whose output is structurally constrained to satisfy the Carnot upper bound. The fundamental thermodynamic constraint is: $COP_{Carnot} = \frac{T_{cond}}{T_{cond} - T_{evap}}$, where T_{cond}, T_{evap} – condensing and evaporating temperatures (~5 K and ~5-10 K respectively) in Kelvin.

The PINN architecture is a tree-hidden layer feedforward artificial network with ReLU activation function, having five inputs (x_{HP}), and tree outputs (y_{HP}) vectors:

$$x_{HP} = \left[T_{amb},\ T_{sup},\ T_{ret},\ \dot{m}_w,\ s\right]^T$$

$$y_{HP} = s \cdot [y_{COP}, Q_{HP}, Q_{el}]$$

T_{amb} – outdoor ambient temperature [K], T_{sup}- ASHP supply water temperature [K], T_{ret}- ASHP return water temperature [K] $\dot{m}_w$ – ASHP water circuit mass flow [kg/s], s – compressor state [1/0 – ON/OFF], y_{COP} – predicted ASHP COP, Q_{HP} – thermal power delivered by the ASHP, Q_{el} – electric power consumption of ASHP.

B. Methane Gas Condensing Boiler — Semi-Empirical Model

The instantaneous boiler thermal output is expressed as:

$$\dot{Q}_{GB} = \dot{V}_{gas} \cdot H_{LHV} \cdot \eta_{th}(T_{ret}, PLR)$$

where $\dot{V}_{gas}$ [m³/h] is the volumetric gas consumption rate, $H_{LHV} = 9.97$ kWh/m³ is the mean lower heating value of natural gas G20 (considered for Romania), and η_{th} is the thermal efficiency as a function of return water temperature (T_{ret}) and Partial Load Ratio (PLR). The efficiency is computed according to the two fundamental functioning regimes, defined by the dew point temperature T_{dew}, as follows: $\eta_{th} = \eta_{nc}(PLR) + (\eta_{c,\,max} - \eta_{nc}(PLR)) \cdot f_{cond}(T_{ret})$ and

$$f_{cond}(T_{ret}) = \frac{1}{1 + \exp[\kappa(T_{ret} - T_{dew})]}$$

where T_{dew} = 55 °C is the flue gas dew point (stoichiometric CH_4 combustion, 10% excess air), $\kappa = 0.15$ $°C^{-1}$ is the sigmoid steepness calibrated against the manufacturer's rated conditions, $\eta_{c,\,max} = 1.05$ (condensing, 50/30 °C) and $\eta_{nc} = 0.97$ (non-condensing, 80/60 °C).

The partial-load efficiency follows a quadratic function of $PLR = \dot{V}_{gas}/\dot{V}_{gas,\,nom}$: $\eta_{nc}(PLR) = \eta_{nc,\,rated} \cdot (a_0 + a_1 \cdot PLR + a_2 \cdot PLR^2)$ and coefficients $a_0 = 0.935$, $a_1 = 0.110$, $a_2 = -0.045$ ($R^2 = 0.992$), fitted to four manufacturer partial-load operating points.

In line with the primary objective of reducing fossil fuel consumption, the HVAC system operation will be optimized through its digital counterpart using an AI-augmented control strategy based on rule-based decision logic. It is expected that this approach will limit the functioning of the methane gas boiler to a limited set of operating conditions, specifically when the computed coefficient of performance (COP) of the AWHP falls below a predefined threshold or when natural gas consumption is economically favorable compared to grid electricity, accounting for both energy efficiency and real-time tariffs constraints. In the remaining operating scenarios, the heat demand could be met using the air-source heat pump and on-site photovoltaic electricity. Concretely the DT's AI agent will prioritize stored heat first, then uses renewable PV electricity when available, and makes economic/efficiency decisions between the heat pump and gas boiler based on COP and cost comparisons, as depicted in the following pseudocode:

```
START

REPEAT:
  IF interior temperature drops under threshold:
    IF hot water tank could provide the required heat:
      use the heat stored in the tank
      CONTINUE to START
    ELSE:
      IF PV panels produce electricity:
        use the ASHP with PV electricity
        CONTINUE to START
      ELSE:
        IF AWHP COP is greater than threshold:
          IF required quantity of natural gas is less expensive than required
electricity:
            use the GB
            CONTINUE to START
          ELSE:
            use the AWHP with grid electricity
            CONTINUE to START
        ELSE:
          IF PV panels produce electricity:
            use electric resistance with PV electricity
            CONTINUE to START
          ELSE:
            use the GB
            CONTINUE to START
  ELSE:
    do nothing for 10 minutes
    CONTINUE to START
```

Fig. 2. Pseudocode of the hybrid HVAC system functioning

To achieve these facts through digital twin technology, it is required to have accurate information about the functioning parameters of the physical hybrid system. For this, a robust energy management and data acquisition solution that enables high fidelity and real-time monitoring was identified. This open-source monitor combines a precision multi-channel electrical measurement interface with an embedded processing unit (a Raspberry Pi board computer), facilitating continuous logging, local and remote data visualization, features required for advanced energy systems' monitoring.

The monitoring system, encompassing both hardware and software, is especially well suited to research contexts where sensor signals must be integrated into hybrid system models. For the proposed hybrid HVAC configuration, the monitoring system will harvest the instantaneous electrical consumption of the heat pump and other loads, as well as PV production and temperature dynamics. These measurements feed directly into the digital twin's state estimator and machine learning-based agent, providing the empirical grounding needed to optimize control actions that mitigate methane gas consumption and maximize renewable electricity utilization as described in your preceding paragraph. Besides our DT, the data will be sent to https://heatpumpmonitor.org, an open-source initiative to share heat pumps performance data, where more than 250 systems are continuously monitored and the performances shared within the community and different stakeholders.

Additionally, a system-level diagram was designed to define the overall architecture and sensor placement, succeeded by a concise description of the key qualities, their units and the medium where data aggregation happen – on edge devices, cloud or in a hybrid setup – together with a discussion of practical issues related to data degradation over time (sensor drift, missing data, communication losses, calibration decay). Fig 3. depicts the digital counterpart of the physical system and the sensors' placement.

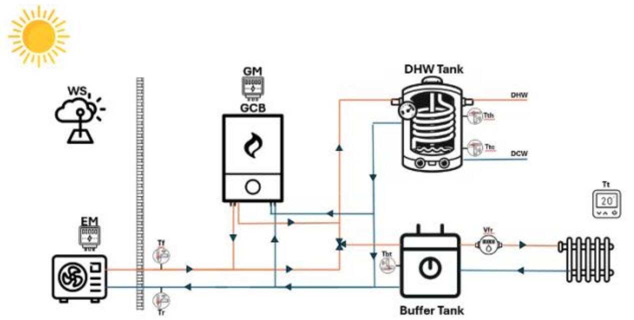

Fig. 3. The Digital Twin representation and sensors' placement

To integrate mathematical modelling, optimization and AI techniques, the following parameters will be measured and analyzed through a Modbus communication interface:

- heating supply water temperature (°C) – Tf /Tr (flow/return) - ultrasonic heating and cooling energy meters
- boiler tank top & bottom temperatures (°C) – Tth/Ttc (hot/cold) - probes on tank shell (top/bottom)
- buffer tank flow temperature (°C) – Tbt - probes on buffer tank shell
- ambient temperature (°C) - Tt
- water flow rate (L/min or m^3/h) – Vfr (consumer side) - clamp-on ultrasonic flow meter (external transducers)
- heat pump electrical power (W) - 2x single-phase 45A
- Gas consumption (m^3) – gas meter
- Meteorological Parameters – WS (weather station)
  - Air temperature (°C)
  - Relative humidity (%RH)
  - Atmospheric pressure / barometric pressure (hPa)
  - Wind speed (m/s, km/h) and gust speed
  - Wind direction (degrees, °)
  - Precipitation / rainfall (mm)

The solution for data management is comprised of a hybrid setup, to leverage time-critical data locality of an edge device and heavy analytics, long term storage and model upgrades of a cloud setup. The edge device design is made up of a RaspberryPi minicomputer for complex operations and a microcontroller for sampling and simple calculations. To mitigate sensor drift and missing data, an alerting system based on drift detection (rolling baseline, control charts, change-point alarm etc.) will be developed and integrated within the DT. The main functionality of the digital twin is to model the physical-based representation of the system and be able to approximate unmeasured states. These predictions serve as the core input for the optimization and control modules. Short term forecasts are then transformed into precise actions and rules to resolve the defined operational objectives (comfort, energy cost, COP, emissions, equipment wear), functioning based on the following control strategy.

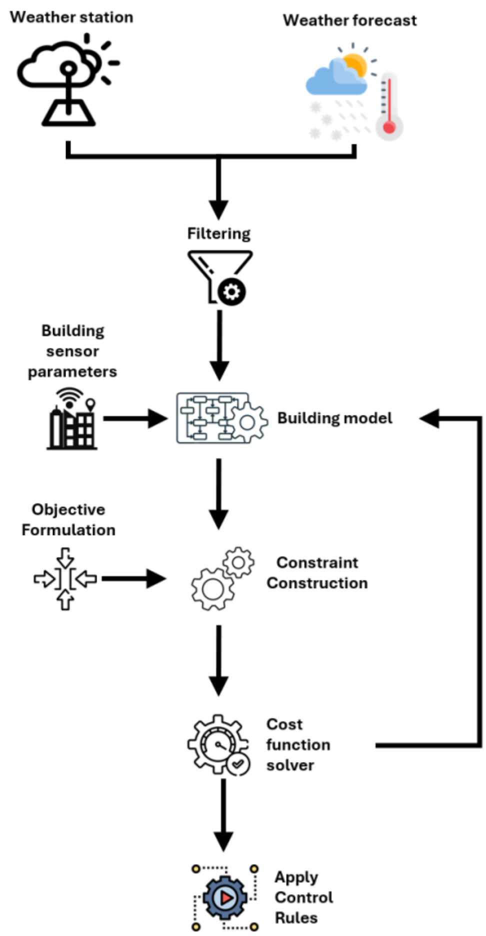

Fig. 4. Digital Twin's proposed control strategy diagram

This general framework for control strategy incorporates 5 core steps that produce an optimal future setpoint. Future thermal loads are anticipated by incorporating weather forecasts and internal gains. The building is represented by a dynamic model, and at each interval a solution to an optimization problem, to minimize energy cost while enforcing comfort constraints is obtained. Optimization is repeated to correct disturbances in forecast errors.

Additionally, for better understanding the system's behavior, data visualization application(s) will be developed. Interactive time-series charts will be designed to aid the users in comparing multiple metrics: measure vs. predicted behavior, events (defrost cycler, setpoint changes etc.) and means to spot drifts or anomalies. A special panel will be dedicated to alerts, explanations (threshold breach, change-point detection, sensor fault etc.) and recommended actions. Moreover, various filters will allow the user to select dates and interact with the operation modes, weather conditions and other metrics of interest. In the end everything should be reportable in the required formats.

All the data will be displayed using Grafana dashboard, which can provide high-level view of how the building's thermal environment and HVAC system behave over time by combining operating-state indicators with multiple temperature trends on one screen. It allows the users to visualize the system's functionality, how target settings relate to measured conditions, how temperatures evolve across different locations, and how those patterns compare with outdoor conditions. This enables quick monitoring of comfort and system behavior and helps spot patterns or anomalies fast.

Anomaly detection for a HVAC system can be achieved with a dual (physics + machine learning) approach. A data driven model (Long Short Term Memory Artificial Neural Network or autoencoders) is trained with the system's normal operation of sensor measurements and an anomaly flag is produced when the reconstruction/prediction error is high. Additionally, physical constraints enforce hard rules that make detections realistic, for example (energy limits, COP/efficiency, mass-flow continuity, temperature ranges) reduce false alarms and unusual operation regimes detections.

IV. CONCLUSIONS

This paper presents the conceptual framework and early-stage development of HESTIA, a digital twin-enabled control platform for a hybrid HVAC system integrating an air-source heat pump, a methane-fueled wall-mounted boiler, a heat storage tank and PV panels. The proposed architecture addresses a critical gap in the decarbonization pathway for the existing residential buildings (but not limited to), particularly in regions where natural gas heating remains predominant, such as Romanian region. The HESTIA experimental infrastructure, comprising an 8kW monoblock R290 heat pump, a 20kW condensing gas boiler, thermal storage units, and PV generation capacity, provides an unique testbed for systematic investigation of hybrid heating system performance.

The proposed digital twin architecture leverages physics-based modeling combined with data-driven techniques to enable real-time state estimation, predictive simulation, and optimization-based control. The modular framework incorporates weather forecasting, thermal load prediction, and multi-objective optimization to minimize energy costs and fossil fuel consumption while maintaining occupant comfort.

Key contributions of this work include:

- the development of an integrated experimental platform specifically designed for HVAC 's digital twin validation.

- a scalable control architecture combining predictive optimization with anomaly detection.

- a comprehensive monitoring strategy addressing the unique challenges of hybrid HVAC systems. The incorporation of dual physics-based and machine learning approaches for anomaly detection represents an innovative approach which ensures system's reliability, while identifying performance faults in order to maximize functionality.

Future work will focus on completing the experimental campaign, validating the digital twin models against measured data, and quantifying the energy savings and emission reductions achievable through optimized control strategies.

The HESTIA framework provides a replicable pathway for retrofitting existing gas-heated buildings with heat pump technology while leveraging digital twin capabilities to optimize performance, reduce operational costs, and accelerate the transition toward intelligent, sustainable building energy systems. Moreover, the proposed functioning strategy it will assure a drastic reduction in the methane gas consumption and increase in PV generated electricity usage.

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REFERENCES

[1] Y. Lu, *et al.* "Digital Twin-Driven Smart Manufacturing: Connotation, Reference Model, Applications and Research Issues," *Robotics and Computer-Integrated Manufacturing*, vol. 61, Art. no. 101837, 2020.

[2] M. Dongellini, C. Naldi and G. L. Morini, "Influence of sizing strategy and control rules on the energy saving potential of heat pump hybrid systems in a residential building", Energy Conversion and Management, vol. 235, 2021 (114022)

[3] E. Roccatello, *et al.* "Analysis of the Influence of Control Strategy and Heating Loads on the Performance of Hybrid Heat Pump Systems for Residential Buildings." Energies, vol. 13(5), 2022

[4] N.I. Ibrahim, *et al.*, "State-of-the-art of the digital twin concept in HVAC+R systems for thermal management of buildings", Renewable and Sustainable Energy Reviews, Vol. 229, 2026 (116601)

[5] E. Zanetti, , *et al.*, "Commercial building HVAC demand flexibility with model predictive control: Field demonstration and literature insights", Energy and Buildings, Vol. 345, 2025 (116097)

[6] B. Arsecularatne, *et al* "Digital Twins for Reducing Energy Consumption in Buildings: A Review". Sustainability, Vol 16, 2024

[7] R. Bortolini, *et al.* "Digital Twins' Applications for Building Energy Efficiency: A Review", Energies, vol. 15, 2022 (7002)

[8] M. Boukaf, *et al.*, "A Comprehensive Review of Digital Twin Technology in Building Energy Consumption Forecasting," *IEEE Access*, vol. 12, 2024

[9] S. Abrazeh *et al*., "Virtual Hardware-in-the-Loop FMU Co-Simulation Based Digital Twins for Heating, Ventilation, and Air-Conditioning (HVAC) Systems," in *IEEE Transactions on Emerging Topics in Computational Intelligence*, vol. 7, no. 1, pp. 65-75, Feb. 2023

[10] L. Ruixin, *et al.* "A high-fidelity digital twin predictive modeling of air-source heat pump using FCPM-SBLS algorithm", Journal of Building Engineering, Vol. 87, 2024 (109082)

[11] J. Uche, *et al.* "Configurational Design of a Hybrid System Based on an Air–Water Heat Pump and Biomass Boiler for a Rural Dwelling". Appl. Sci., vol. 14, 2024 (9840).

[12] Y. Mao, *et al.* "Research on the Configurations and Control Methods of a Hybrid System of Air-Source Heat Pumps and Gas Boilers for Space Heating: Simulation and Comparative Analysis", Sustainability, vol. 17, 2025 (6173)

[13] M. Saffari, *et al.* "Technical and economic assessment of a hybrid heat pump system as an energy retrofit measure in a residential building", Energy and Buildings, vol. 295, 2023 (113256)

[14] F. Nicoletti, *et al.* "Optimal operating strategy of hybrid heat pump − boiler systems with photovoltaics and battery storage", Energy Conversion and Management, vol. 323, Part A, 2025 (119233)

[15] A.-M Bulmez *et al.* "An Analysis of Romania's Energy Strategy: Perspectives and Developments since 2020", Climate, vol. 12, 2024