U.P.B. Sci. Bull., Series C, Vol. 88, Iss. 2, 2026 ISSN 2286 – 3540

HYBRID ENERGY SYSTEM WITH DIGITAL TWIN AUGMENTATION. THE HESTIA CONCEPT

Horia NECULA [1], Mihail-Bogdan CĂRUȚAȘIU [2*], Virginia PETRE[3]

The HESTIA proof of concept aims to develop an experimental infrastructure for the analysis of a complex heating/cooling system optimized and operated by its digital counterpart through detailed dynamic modeling. This will allow to estimate and validate the impact of digitalization on the reduction of fossil fuel consumption in existing buildings. The experimental installation will consist of an air-to-water heat pump, a natural gas boiler, a PV system, a boiler for thermal energy storage and a high-performance data acquisition system. Moreover, a digital twin will be developed to ensure an optimal operation of the system and to allow virtual analysis of other similar systems. The HESTIA concept also aims to identify the best strategies for using both the whole system and its component to minimize the consumption of natural gas and electricity from the national grid, while also maximizing the use of the heat pump powered by the electricity from the panels PV.

Keywords: hybrid HVAC prototype, digital twin, energy efficiency

1. Introduction

The buildings are responsible for up to 40% of the total energy usage and approximatively 36% of energy related direct greenhouse gas emissions across EU countries [1]. These percentages are mostly due to the large energy consumption of the integrated heating, ventilating, and air conditioning (HVAC) systems, as their operation still relies heavily on fossil fuels – more than 55% of buildings' final energy consumption. In conjunction with the fact that nearly 75% of the buildings across EU are energy inefficient, mitigating this sector's impact is treated as a high priority task by the EU Council [1]. Additionally, the final goal of all EU strategies and legislation packages are very ambitions and propose zero net greenhouse gases emissions by 2050 through European Grean Deal [2] and, intermediary, up to 55% reduction by 2030 through Fit-for-55 [3]. However, it's impossible to meet these bold targets without curbing the existing buildings' emissions because more than 220 million building units (85% of the EU's building stock) are old (built before 2001) and energy inefficient [4]. These facts also apply in Romania, as a large share

---

[1] Prof., Dept. of Energy Generation and Use, NUST POLITEHNICA Bucharest, Romania, e-mail: horia.necula@upb.ro

[2*] Lecturer, Dept. of Energy Generation and Use, NUST POLITEHNICA Bucharest, Romania, corresponding author, e-mail: mihail.carutasiu@upb.ro

[3] Lecturer, Dept. of Energy Generation and Use, NUST POLITEHNICA Bucharest, Romania, e-mail: virginia.petre@upb.ro

of the existing buildings are old (more than 90% were built before 1989) and about one third of them require retrofitting [5]. This emphasis the urge to undergo a transition toward a low-carbon energy systems in this crucial sector.

Recent advances in digital twins (DT) and model predictive control (MPC) have opened new avenues for real-time optimization, reliability, and efficiency. In this given context, the scope of the Hybrid Energy System with Digital Twin Augmentation (HESTIA acronym) proof of concept is to develop an experimental infrastructure of a complex hybrid HVAC system optimized and operated by its digital counterpart through detailed dynamic modelling, thus validating its impact on decreasing the fossil fuel consumption in existing buildings. To achieve this, a demonstrative experimental project will be developed. This approach is designed to respond to one of the Romanian Areas of National Intelligent Specialization challenges, namely the third main domain: Energy, environment, and climate change. It will also address issues stated in the following subdomains: *smart energetic management*, *zero energy buildings* (ZEB), *energy efficiency and security*, *energy in buildings' sector* and *information and communication technologies*. Furthermore, by developing this emergent technology with cross-cutting impact on local and regional levels as an innovative ecosystem, this project will tackle one important social challenge from the 2022-2027 Romanian National Strategy for Research, Innovation and Smart Specialization [6]: Climate, energy, and mobility: "*development of environmentally friendly technologies in obtaining new energy storage solutions; new methods and technologies for producing energy from renewable resources with a low carbon footprint and their large-scale implementation; integration of renewable energy sources in heating and cooling systems; digitization of the energy system".*

Even if this kind (or small variations) of heat pumps assisted by gas boilers HVAC systems were analyzed in recent scientific literature, as can be found in papers from Ref. [7], [8], [9], [10] to list a few, the digital twin integration lacks entirely. Moreover, the number of air-source heat pumps is lower than the ground source types [11]. The study from J. Seifert et al. [12] describes the development of a digital twin of a heat pump, but their system does not contain the fossil fuel equipment. Besides these, no optimization strategies were presented in the reviewed papers, thus the need to address these.

In some recent reviews, such as the work of G. Bortolini, et al [13] and K. Samykano et al. [14] highlight the increasing adoption of DT systems in building energy systems and hybrid PV–heat pump architectures, also identifying an important research gap in integrated experimental validations. Laboratory-scale setups have been used to analyze a thermal energy storage systems integration with DT [15]. Moreover, Evens et al. [16] and Rutkowski et al. [17] integrated neural-network-based models within DT, increasing the capability of real-time predictions. This bridged the gap between physics-based accuracy and computational efficiency, concluding that the considered AI models could reduce operational costs, while also increasing the overall building's energy efficiency.

2. The physical system

The central point of the HESTIA system is the development of an experimental hybrid HVAC system. This complex technology will replace the heating system in one large office (approximatively 70 m^2) in the Faculty of Energy Engineering, located in the proximity of the Industrial Thermal Equipment and Installations Laboratory in National University of Science and Technology POLITEHNICA Bucharest. To accomplish this, the following equipment will be integrated: an air-source heat pump (ASHP), a natural gas boiler (GB), a buffer storage tank (ST), a photovoltaic (PV) system, water flow system (pumps, ducts, joints etc.), radiators and automations (controls, relays, switches etc.), The dimensioning of these equipment will be determined through numerical simulations using complex mathematical models integrated within mature and specialized computer programs. For this, the following software were identified: RETScreen, TRNSYS, PVSyst and GeoT*SOL.

This heat poly-generation and storage configuration was designed considering two important aspects: first, natural gas boilers are the most used heating systems in Romanian buildings (estimated at more than 2.5 million units [18]) and secondly, the ASHP have reduced heating capacity at low evaporation temperatures, as it is in cold periods [11]. Strategies regarding the natural gas consumption mitigation will be implemented through a data acquisition system composed of temperature sensors, flow meters, energy meter, weather station data storage and analysis server. Basically, the proposed configuration has three different ways to produce and store heat in the buffer tank: ASHP, GB heating water and backup electric resistance respectively. This will increase the system's resilience to quick thermal fluctuations due to the tank's high thermal inertia. The PV system will decrease the grid power consumption of both heat pump and electrical resistance based on a logical threshold AI-augmented decisional algorithm. This configuration allows testing the best strategy to minimize the usage of fossil fuels (as natural gas and grid power) and maximize the usage of the electricity generated from the PV panels to power the heat pump. The hybrid system's key components interconnectivity is depicted in Fig. 1, offering insights about the energy flows and sensors placement.

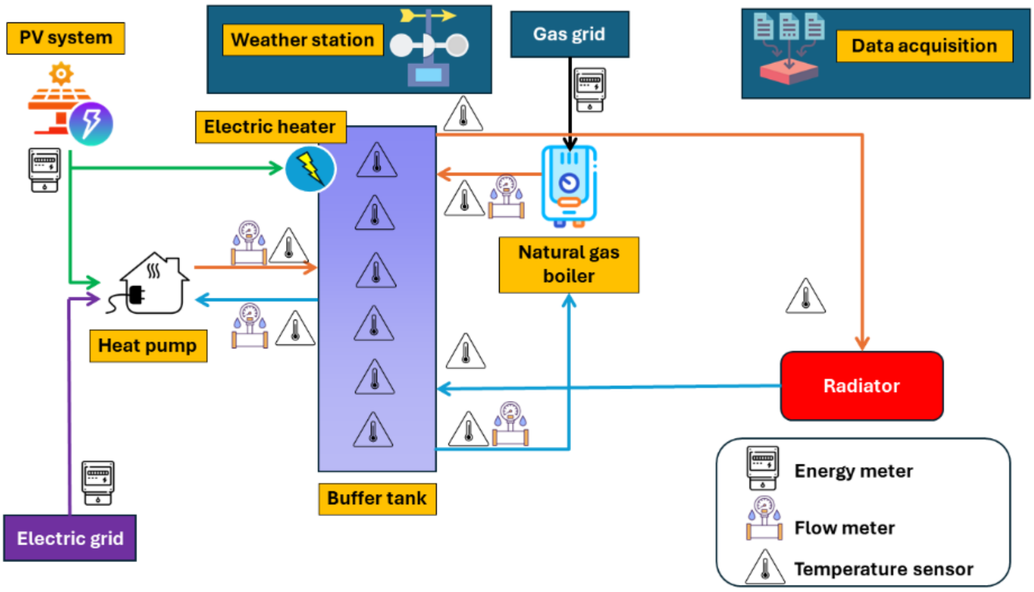

Fig. 1. Experimental setup of the complex hybrid HVAC system and the sensors' placement

The above-mentioned configuration assures the optimal functionality of the hybrid HVAC, and it comprises all the required equipment for maintaining the indoor climate at required parameters. The heat pump is connected at two different electricity sources: the local electric grid and the local mounted PV system. This way, the digit twin cand choose the best supply option based on energy availability and electricity price. Each electricity supply option will be monitored by an energy meter. The natural gas boiler will be connected to the local natural gas network and monitored by a IoT natural gas meter which will transmit data in real time. Both the heat pump and natural gas boiler will be connected to the buffer tank which will store the hot water provided. Based on HP's COP, the electricity and natural gas prices, the instantaneous heat requirement, the digital twill will decide which equipment will be used to fill the tank with hot water, consequently minimizing the fossil fuel consumption. Additionally, several flow meters and temperature sensors will provide thermal and mass information about the working fluid and hot water thermal stratification. The data acquisition system and weather data are essential for the digital twin counterpart as it should be able to run complex data-driven mathematical optimization models.

This configuration allows testing the best strategy to minimize the usage of fossil fuels (as natural gas and grid power) and maximize the usage of the electricity generated from the PV panels to power the heat pump. The hybrid system's key components interconnectivity is depicted in Fig. 1, offering insights about the energy flows and sensors placement.

3. The digital twin

Besides the above-mentioned experimental setup, a modern used-friendly digital twin will be developed, representing a virtual replica of the physical system continuously updated with real-time data [19]. This will allow the transition towards the digitalization of similar hybrid HVAC systems resulting in a digital hybrid HVAC system. The digital twin will have two distinct functionalities. First, it will assure the system's optimal functionality through advanced monitoring, dynamic modeling, automatic fault detection and diagnosis, consumption forecasts and reporting. Additionally, it will decide on the adequate equipment utilization to decrease the natural gas consumption of the natural gas boiler also considering price restrictions. Secondly, it will allow creating different virtual scenarios to test various functionalities of the hybrid HVAC system or even simulate the performances of other equipment, increasing the concept's utility and applicability. Functionally, a digital twin has three components: hardware (sensors, network devices, servers), software (models, dashboards, design tools and/or interconnected simulation software) and data management system (centralized repository, data science) [19]. Thus, the interconnectivity between the real and virtual systems and data flow are shown in Fig. 2.

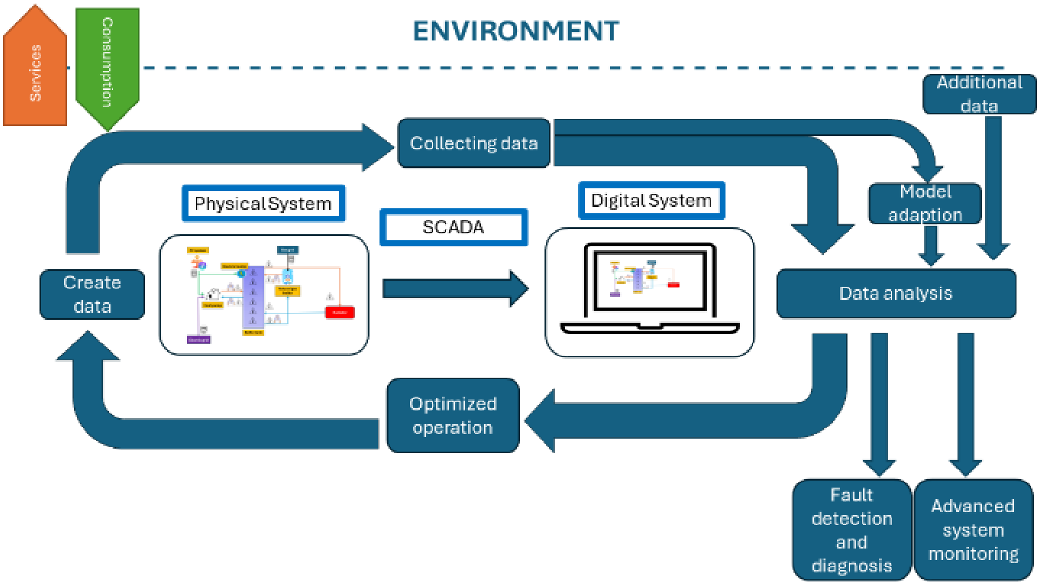

Fig. 2. Physical system and digital twin interaction

The HESTIA digital twin will include a 3D representation of the physic hybrid HVAC system's components, including ducts, vents, pumps, pipes, and fittings together with their specific placement in the physical system. This will be implemented using the Unity 3D Game Engine Framework. This digital 3D interface will be continuously fed with data from sensors through data acquisition system and the interconnectivity will be facilitated by a developed SCADA system architecture. In addition, the digital twin will facilitate the possibility to analyze the system's response to different regimes and operation strategies, and external condition, through complex dynamic regime mathematical modelling. It will include the control algorithms for optimal HVAC system operation considering different temperature setpoints, schedules, thermal loads, available energy resources and their prices. This will be achieved using rules base decision-making algorithms such Artificial Neural Networks (ANN). Furthermore, the digital twin will incorporate AI area-based models to assure complex functionalities such as predictive control, performance monitoring fault detection. Moreover, given the main scope of the experimental setup (lowering the fossil fuel consumption), the HVAC system's functionality will be also optimized by an AI augmented model based on logical rule-based statements presented in Fig. 3.

Fig. 3. Decision making diagram

The complex system's analysis will choose between six functionality cases, which are, in fact, all the possible energy supply scenarios. There are classified from best to worst scenario, where the best configuration is represented by the HP functionality supplied by the PV panels, while the worst scenario is the functionality of the natura gas boiler. Therefore. the first think is to check if the desired interior temperature is met. If this is true, do nothing for a determined period (10 minutes). If not:

Scenario 1: if there is enough hot water in the buffer tank, it should be used with priority (no additional energy will be required).

Scenario 2: if heat is required, the computed HP's COP is above an imposed threshold, and the PV panels produce enough electricity (or the battery has the required amount of energy stored), use the HP in conjunction with PV.

Scenario 3: if heat is required, the computed HP's COP is above an imposed threshold, and the PV panels does not produce enough electricity (or the battery has not the required amount of energy stored), use the HP in conjunction with the grid electricity – only if the required quantity of natural gas is more expensive than the electricity bought from the grid.

Scenario 4: if heat is required, the computed HP's COP is above an imposed threshold, and the PV panels does not produce enough electricity (or the battery has not the required amount of energy stored), use the GB - if the required quantity of natural gas is less expensive than the electricity bought from the grid.

Scenario 5: if heat is required, the computed HP's COP is below an imposed threshold, and the PV panels produce enough electricity (or the battery has the required amount of energy stored), use the buffer tank's electric resistance in conjunction with the PV system.

Scenario 6: if heat is required, the computed HP's COP is below an imposed threshold, and the PV panels does not produce enough electricity (or the battery has the required amount of energy stored), use the GB.

Thus, the proposed strategy will permit the usage of the BG equipment only in two out of six cases:

1st case: the AHPS' computed COP (coefficient of performance) does not meet a required threshold value.

2nd case: the natural gas quantity consumed is less expensive than the electricity needed from the power grid, lowering this way the overall natural gas consumption but also considering the energy costs at a given time.

In contrast, in three out of six cases, the ASHP or the PV electricity was used. To achieve this feature, it is necessary to dynamically simulate the hybrid system, an exceedingly challenging task to do, due to its high complexity. The approach to mitigate this inconvenience is to model the key components (ASHP, GB, ST, PV) separately and then compose the entire system finally. This makes possible the design of the control framework and verify both individual components and whole system's performance effectively.

To this end, first-order delayed transfer functions will be employed to represent the dynamics of each constituting component of the hybrid HVAC system. This innovative system's optimal functionality will be assured by a complex Artificial Neural Network trained based on different operation strategies implemented through the digital twin platform.

4. Conclusions

Concluding, this concept's high novelty degree is assured by the innovative system composed of the hybrid HVAC technology and the digital instrument (twin) used for both system's optimal functionality and virtual testing. It is worth mentioning that the proposed approach goes beyond the national state of the art, as there is no national experimental infrastructure to analyze hybrid HVAC systems nor developed digital twins to further test different equipment configurations, allowing to explore this topic in a new and innovative way.

Moreover, the HESTIA implementation expected outcome is to expand the application field of existing ASHP, PV and thermal storage technologies to mitigate the fossil fuel consumption in existing buildings. It will directly contribute to the increase of the installed ASHP capacity, which currently is at only 197 GW across EU, despite 41% sales growth in 2021 [20]. Moreover, the global digital twin market size (in terms of revenue) was approximately 10 USD billions in 2023 growing from 6.8 USD billions in 2022 and forecasted to value up to 110 USD billions by 2028 [21], arguing the HESTIA feasibility. Moreover, the digital twin generated data will create a new business line by adopting Data as a Service (DaaS) model, as it has great potential in this big data era.

The main objective of the HESTIA project is to demonstrate the potential of using digital hybrid HVAC systems to decrease the carbon footprint of existing buildings, also increasing the innovation capabilities of potential stakeholders. For this, besides increasing the TRL form 2 (concept) to 4 (validated technology) of an experimental hybrid HVAC system with high integrability in existing buildings, we estimate a maximum 60% reduction of the fossil fuel equipment usage. Moreover, extending the functionality of the physical system by augmenting it with a digital twin, which could decrease the additional systems investment payback with more than 50%, expanding the project's utility beyond its implementation or sustainability period by assuring its adaptability.

The HESTIA project's expected outcome is to expand the application field of existing ASHP, PV and thermal storage technologies to mitigate the fossil fuel consumption in existing buildings. For this, the hybrid HVAC system's feasibility (without considering the optimized functionality) was estimated in another research paper, concluding that if the electricity price is 1.0 RON/kWh and the natural gas price is 0.5 RON/kWh, the simple payback of integrating an 8 kW ASHP with COP of approximately 2, is less than 6 years. It is expected that, by optimizing the systems functionality with the developed digital twin, the payback period will be reduced by more than 50%.

This digital system can be adapted for a range of local building types ranging from small to large, residential to commercial, ensuring broad applicability and scalability. Additionally, the HESTIA modular configuration will allow the analyzing the integration of ASHP with other heat sources, as the predominant global trend is to limit the utilization of GBs. Thus, new emerging systems could be used – for example a hydrogen fuel cells or hydrogen-fired boilers, which currently is not a cost-effective technology. In this possible configuration, the PV system could be used for both hydrogen generation and ASHP functionality, slightly adapting the decision-making algorithm from Fig. 3. This will expand the concept's utility beyond its implementation or sustainability period by assuring its adaptability.

Acknowledgement

This paperwork was funded by a grant of the Ministry of Research, Innovation and Digitization (UEFISCDI), project No. **92PED/2025** (PN-IV-P7-7.1-PED-2024-2504), through "Demonstration Experimental Project" call, Program 5.7 (Partnership for Innovation), Subprogram 5.7.1 (Partnerships for competitiveness).

REFERENCES

[1] https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en

[2] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[3] https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0662

[5] https://www.roenef.ro/wp-content/uploads/2018/09/EPG_ROENEF_Studiu-eficienta-energetica-in-cladiri.pdf

[6] https://www.poc.research.gov.ro/uploads/2021-2027/conditie-favorizanta/sncisi_19-iulie.pdf

[7] Taler D., Pitry R., Taler J. Operation assessment of hybrid heat source for heating the building and preparation of hot water in the fire brigade building. J Cleaner Prod 2019; 214:962–74.

[8] Dongellini M, Naldi C, Morini GL. Influence of sizing strategy and control rules on the energy saving potential of heat pump hybrid systems in a residential building. Energy Convers Manage 2021; 235:114022.

[9] Zanetti E, Aprile M, Kum D, Scoccia R, Motta M. Energy saving potentials of a photovoltaic assisted heat pump for hybrid building heating system via optimal control. J Build Eng 2020; 27:100854.

[10] Calise F, Figaj RD, Vanoli L. A novel polygeneration system integrating photovoltaic/thermal collectors, solar assisted heat pump, adsorption chiller and electrical energy storage: Dynamic and energy-economic analysis. Energy Convers Manage 2017; 149:798–814.

[11] M. Beccali, M. Bonomolo, F. Martorana, P. Catrini, A. Buscemi, Electrical hybrid heat pumps assisted by natural gas boilers: a review, Applied Energy, Volume 322, 2022,

[12] J. Seifert, L. Haupt, L. Schinke, A. Perschk, T. Hackensellner, S. Wiemann, M. Knorr, Digital Twin for Heat Pump Systems - Description of a holistic approach consisting of numerical models and system platform, REHVA 14th HVAC World Congress, 22-25 May 2022, Rotterdam, The Netherlands

[13] G. Bortolini, et al., “Digital Twins’ Applications for Building Energy Efficiency,” Energies, vol. 15, no. 12, 2022.

[14] K. Samykano, et al., “Hybrid Photovoltaic Thermal Systems: Present and Future,” Energies, vol. 16, no. 2, 2023.

[15] Z. Lv, et al., “Digital twins for secure thermal energy storage in buildings,” Energy, Elsevier, 2023.

[16] J. Evens, et al., “Heat pump digital twin: An accurate neural network model,” Applied Energy, Elsevier, 2025.

[17] M. Rutkowski, et al., “Digital Twin in the Design and Dynamic Assessment of Energy Systems,” Energies, MDPI, 2024.

[18] https://energie.gov.ro/wp-content/uploads/2022/08/Strategia 2030_DGJRI_AM_12.08.2022_MU_Clean_25.08.2022-1.pdf

[19] M. Liu, S. Fang, H. Dong, C. Xu, Review of digital twin about concepts, technologies, and industrial applications, Journal of Manufacturing Systems, Volume 58, Part B, 2021, Pages 346-361, ISSN 0278-6125

[20] https://www.iea.org/energy-system/buildings/heat-pumps#tracking

[21] https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html