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A digital twin concept for optimizing the use of high-temperature heat pumps to reduce waste in industrial renewable energy systems

Alex Butean[a,c,*], Juan Enriquez[b], Alexandru Matei[a,c], Antonio Rovira[d], Rubén Barbero[d], Silvia Trevisan[e]

[a]*Wiz Research, 4 Samuel Von Brukenthal, Sibiu, 550178, Romania*
[b]*Dynamic & Security Computations SL, 54S1 C Fermín Caballero, Madrid, Spain*
[c]*Lucian Blaga University of Sibiu, 10 Bulevardul Victoriei, Sibiu 550024, Romania*
[d]*Universidad Nacional de Educación a Distancia, Madrid, Spain*
[e]*KTH Royal Institute of Technology, Department of Energy Technology,10044 Stockholm, Sweden*

Abstract

In light of the global industrial sector's steadfast pursuit of sustainable solutions to mitigate carbon emissions and efficiently minimize energy inefficiencies, the significance of novel approaches to energy optimization becomes increasingly evident. This research presents a novel digital twin concept that is designed to enhance the efficiency and effectiveness of high-temperature heat pumps in industrial renewable energy systems. Through the utilization of real-time data and complex computer modeling techniques, our proposed digital twin model seamlessly presents a comprehensive perspective on energy flows. This approach identifies inefficiencies and delivers practical insights to mitigate waste. The incorporation of this approach into pre-existing eco-conscious renewable energy systems has the potential to greatly enhance the effectiveness, predictability, and long-term viability of industrial processes. The empirical findings, obtained from multiple case studies conducted in industrial settings, provide evidence of the potential benefits in terms of energy waste reduction, and maximize the durability of systems. The results of our initial studies provide a foundation for the utilization of digital twin technologies in the field of industrial renewable energy systems optimization, representing a significant advancement towards a more environmentally sustainable industrial landscape.

Keywords: digital twin; complex systems; simulations; renewable energy; heat pumps; process heat; decarbonization;

* Corresponding author.
E-mail address: alex@butean.com

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1. Introduction

Industry decarbonizing requires a fresh perspective on designing every aspect of the energy supply chain across different sectors. The shift from fossil fuel-based technologies, known for their flexibility in providing energy across wide temperature ranges, to renewable technologies constrained by resource availability and heat temperature, necessitates resource and process optimization, including managing excess and waste energy. Heat upgrade technologies are gaining importance as a solution to meet the high thermal energy demands of industries, offering a dual benefit: reducing fossil fuel consumption and greenhouse gas emissions while creating a new market for renewable-based heat for industrial processes. According to a recent study [1], non-metallic mineral, food, and paper industries provide the most potential in using the waste heat.

Although the European Union has been a leader in using solar heat for industrial processes [2], this type of heat contribution is currently limited to temperatures below 150°C due to sector-specific constraints such as weather conditions and land availability. This temperature limitation aligns with the maximum capabilities of conventional heat pump-based heat upgrade technologies, largely due to constraints generated by the used fluids. To advance the widespread adoption of renewable energy technologies at temperatures above 150°C, the next step is to develop heat pumps and integrated technologies capable of reliably supplying intense heat for processes above this threshold, regardless of the renewable source or waste sink, thereby expanding exploitation possibilities.

Integrating various renewable sources, harnessing available waste energy, and introducing thermal storage systems present a potential pathway for managing energy flows, upgrading available heat in sinks, and optimizing resource dispatchability. Optimizing such a complex process in real-time requires advanced computational resources and methods. To be able to achieve this, we are proposing the usage of a digital twin for HT-HP (high temperature heat pumps) optimization to reduce the waste head in industrial renewable energy systems.

The paper continues with a description of the related work in Section 2 and the proposed digital twin concept is presented in Section 3. The ongoing research activities are detailed in Section 4 while Section 5 concludes the paper.

2. Related work

The concept of a digital twin involves the creation of a precise and intricate replica of a physical object or system, such as manufacturing assets or robots. This process encompasses a wide range of aspects, including the design, configuration, state, and behavior of the physical counterpart [3]. Through the provision of information and services based on the current condition, history, and predicted future of the physical object, digital twins are considered to be fundamental building blocks for the future of digital factories. They provide stakeholders with the ability to collaborate and make informed decisions based on the detailed information provided by these advanced technological entities. As digital twins continue to advance, they are expected to evolve from expert-centric tools to autonomous and adaptive entities that can sense and understand their environment, communicate with each other, and ultimately make informed decisions towards their goals [4]. These entities have a broad range of applications in various domains, including training processes [5], product development, and industrial applications. Ultimately, the use of digital twins represents a significant advancement in the field of technology and has the potential to revolutionize the way we approach and interact with the world around us.

A hybrid heat pump (solar and thermoelectric) design was proposed in [6] for a specific container house, using the digital twin as a method to compare different configurations. As they are coupling the heat pump with a specific building, they also include the building information model in the simulation. This study adopts the digital twin as a methodology to handle multiple data sources, mainly simulators and CAD data, to generate different configuration files for the heat pump.

A digital twin for an integrated energy system is presented in [7] and is used day-ahead scheduling and load forecasting. Their twin model is based on a multi-vector energy flow coupled with the information flow model of the energy market. The twin is used to orchestrate the load balancing of energy sources, consumers, and storages, while planning the next day operations based on the current day. The scheduling is done using a deep learning model that learns the optimal day-ahead scheduling based on the historical forecasts and forecasting errors. One challenge of their approach was the physical constraints exploitation with the deep learning model. To overcome this, they used a special constraint enforcement module in the output layer of their deep learning model.

A generic digital twin architecture (GDTA) for industrial energy systems is proposed in [8]. This abstract architecture is technology independent and follows closely the information technology layers of the Reference Architecture Model Industry 4.0 (RAMI4.0) [9], being inspired from 5C architecture for cyber-physical-systems [10]. They also present a proof of concept by instantiating an architecture for a thermal energy storage use-case. The information model is created using semantic web technologies, Resource Description Framework (RDF) and Web Ontology Language (OWL), while the digital twin capabilities are considered as service agents.

Authors of [11] take the GDTA from [8] and further define specific requirements for industrial energy systems since the digital twin concept is currently well established in other domains, like manufacturing [12]. Their research addresses implementation issues not addressed by the GDTA.

3. Proposed concept

3.1. High Temperature Heat Upgrade system

Industrial renewable heat upgrade systems are complex systems with a high level of interdependencies, parameters, and implications requiring process optimization and orchestration. The proposed concept [13] of this paper is part of the ongoing Susheat project [14] and develops a new generation of highly-efficient heat upgrade systems to harvest and store the heat from renewable energies, waste heat and/or ambient for intensive factory processes. An overall reference diagram can be seen in Figure 1. The main components of such a heat upgrade system are:

- **Waste heat Low T** – waste energy source that delivers low temperature heat
- **Low and High T TES** – two thermal energy storage systems for waste energy at low and high temperatures
- **Heat exchangers** – two dedicated customized heat exchangers, one for each thermal energy level
- **Hight T Heat Pump** – a custom made heat pump that can operates with high temperatures
- **Water tank buffers** – two buffers for damping any fast transients to ensure full system flexibility
- **Solar energy collectors** – properly dimensioned and configured solar energy collectors
- **High demand High T** – industrial operations that require high temperatures (between 150 ºC and 250 ºC)

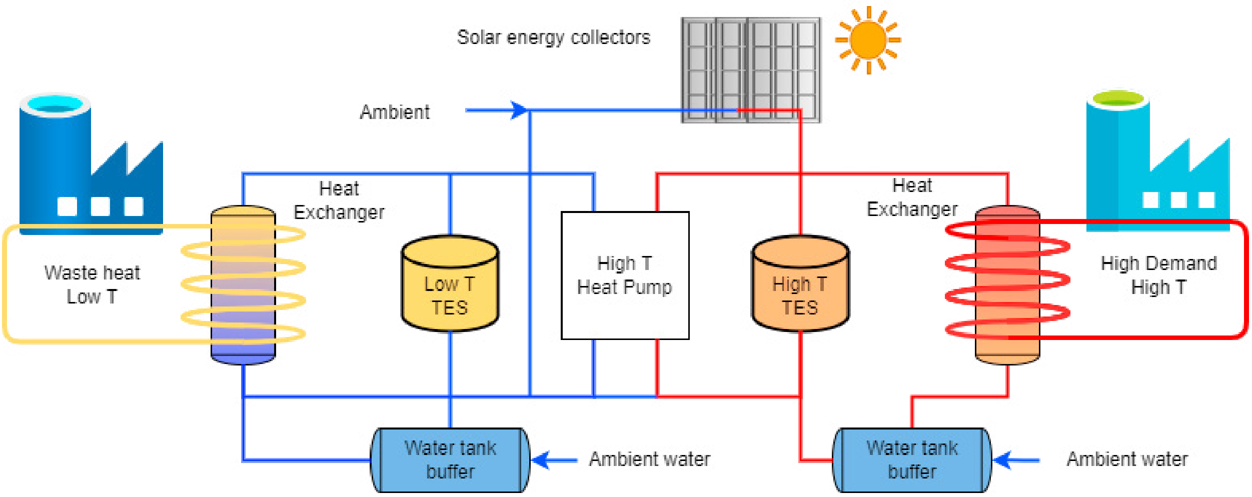

Fig. 1. Reference overall architecture of the proposed concept

The above presented concept is completed with a control system (section 3.2) that integrates all the components and decides which and how much energy from every resource is used to charge the two thermal storage systems, according to their availability, the energy requirements and constraints of specific industries.

3.2. Digital Twin concept

Using renewable energy sources is not an easy task as their reliability is directly influenced by the stochastic forces of nature [15]. Since using a single renewable energy source is not reliable, the approach to reduce this uncertainty is to use a mix of multiple sources coupled with energy storage facilities, resulting in a complex energy system [16]. Another challenge of integrating renewable energy sources is the requirement of a fine-tuned control system that ensures robust and reliable energy output, flexibility in utilizing different variating energy sources, managing the energy storage facilities, or fast recovery in case of malfunctions [17]. The traditional approach of operating such systems with only mathematical models or schemas requires extensive knowledge in the field. The proposed solution is to have a digital twin connected in real-time to high temperature heat upgrade system, allowing for a far more seamless operating experience.

An overview of the digital twin for the high temperature heat upgrade system, together with its main components and basic architectural details are presented in Figure 2.

The main components of the digital twin are:

- The physical artifact of one or more **HT-HPs**
  - Sensors
  - Microcontroller unit
  - Actuators
- **Gateway**
  - Preliminary data processing
  - Local monitor and control interface
- **Digital Control Hub**
  - Data Accumulation
  - Data Abstraction
  - AI Methods (Prediction, Optimization)
  - Remote configuration (for Gateway)
  - UI components (Monitoring, Control, Visual Simulator, Analytics, Reporting)

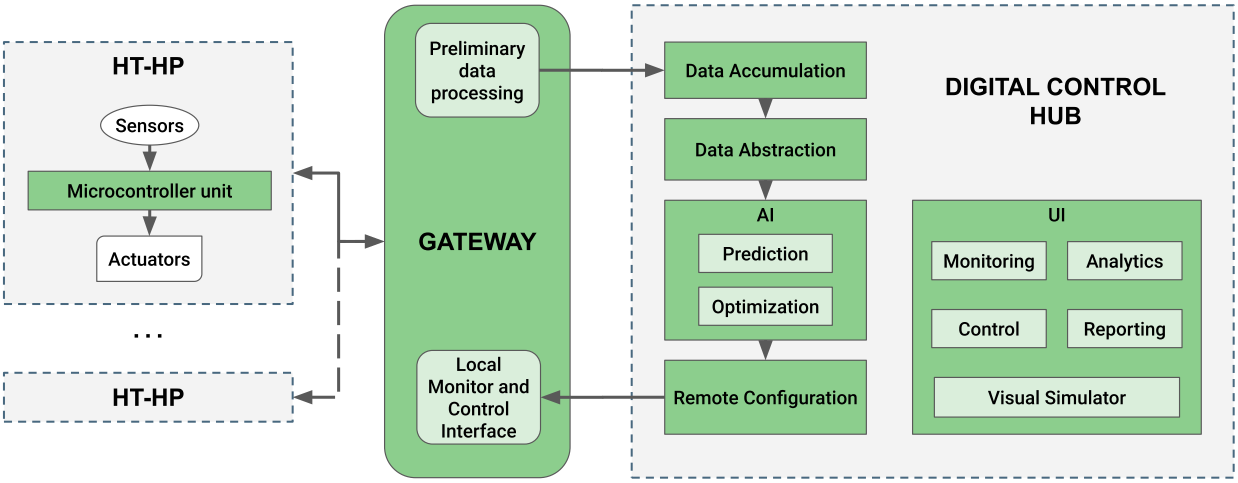

Fig. 2. Proposed Concept of a Digital Twin connected to the High Temperature Heat Upgrade system

The physical artifact of the HT-HP represents a conventional heat pump itself that was visually represented as the core component in the middle of Figure 1. It contains several sensors - temperature, pressure, humidity, and flow - that are used by the microcontroller unit of the HT-HP to close the real-time control loop and command the actuators - compressor, motors, valves, dampers, or fans. The microcontroller is connected to the gateway, a versatile pre-processing unit that connects multiple HT-HP units to the digital control hub.

The main task of the gateway is to create a secure connection of low-level devices with the other application. It can also aggregate data from multiple devices and do preliminary data processing to reduce the number of requests and the volume of data transmitted to the digital control hub. Another responsibility of the gateway is to allow shop floor operators to monitor the HT-HPs and to control them. Through the gateway, the HT-HPs can be configured remotely from the digital control hub.

The digital control hub is a complex application with multiple components. While the gateway resides on-site, usually in the vicinity of where the HT-HPs are located, the digital control hub offers flexibility, and can be deployed either on-site or remotely on the cloud. The data received from the HT-HPs through the gateway is stored in a database by the Data Accumulation components. The Data Abstraction component processes the data stored in the database and converts it into specific formats required by the UI components or the AI services and algorithms. The AI component is the core of the digital control hub as it contains powerful AI algorithms that are used to make predictions and process optimization using not only HT-HP data but also external information regarding the industrial process, that generates or consumes the heat and other ambient factors. Beside prediction and optimization, the AI algorithms can also process the data to find patterns, anomalies, faults in the systems, select what information to be displayed to the user, or even perform simulations using novel architectures like physics informed neural networks [18]. The Remote Configuration component pushes new device configurations based on either AI optimization results or user input. Another important component of the digital control hub is the UI. The main advantage of the UI and all its subcomponents is that it keeps the human in the loop [19]. This user interface allows the user to visualize the HT-HPs data, either historical or real-time. With the help of AI algorithms, the user can easily analyze the real-world data saved in the database. An expert can also manage and control a multitude of HT-HPs remotely. Finally, the visual simulator, together with the AI capabilities can be used in decision making. Simulations of different scenarios will help operators in choosing the best approach for a given situation. Different HT-HPs can be simulated to see how much an improvement would provide or simulate them in extreme cases.

4. Ongoing research

The concept proposed in this paper is an early-stage version of a complex system that will be perfected, developed, tested, and physically implemented in the next 4 years. While the current architecture offers just an overview of the main components, subsequent versions will feature a much higher granularity in terms of specific subcomponents and capabilities of the system. Considering the novelty, innovation level, technical complexity and integration challenges, the ongoing research perspective is focused on conducting state of the art reviews on scenarios optimizations using artificial intelligence systems, simulations for systems of systems, possible digital twin generators, high detail 3D visualizations and simulation. As an immediate next step, the research group is focusing on creating and organizing the data structures for a first implementation of a complete input-output digital twin that aims to create a first instance of the presented concept. With data structures well defined, we can investigate what are the most suitable AI and ML algorithms for the available data gathered from HT-HPs.

5. Conclusions

In conclusion, industry decarbonizing requires extensive research of novel methods along the entire production chain, focusing on green energy usage and promoting its widespread adoption. As renewable energies have a stochastic behavior, smart energy management systems are required to meet the energy levels required by the industrial processes (financial, speed, supply, and demand perspectives). The current paper explores a method for optimizing and promoting high temperature heat pumps usage in industrial renewable energy systems to reduce the waste energy. The chosen method - digital twin - is a recent concept that is very popular in the manufacturing industry and is also gaining traction in the energy domain.

Our proposed digital twin approach for HT-HP represents a new method of approaching industrial energy systems that allows for energy waste mitigation with the help of real-time data and advanced modeling methods.

Using various AI algorithms, the large amount of data generated will be analyzed to get valuable insights on the processes and operational status of the HT-HP.

A big challenge of engineering digital twins remains the multidisciplinary perspective. A good team of computer scientists, physicists, software engineers and renewable energy systems experts is required to successfully model, develop, and implement a digital twin for industrial renewable energy system applications.

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