GreenSIGMA: Intelligent Management and Advanced Monitoring System for Green Energy Production 4.0

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***Abstract*—The GreenSIGMA - Intelligent Management and Advanced Monitoring System for Green Energy Production 4.0 - project aims to develop an intelligent framework for the management, monitoring, and advanced control of waste-to-energy (WtE) plants. Despite advances in energy sector digitalization, the application of optimization technologies to waste incineration processes remains scientifically and technologically immature. This limitation stems from the recent nature of this market segment, the constant variability of waste fuel profiles, and the technical complexity of incineration processes characterized by multiple interdependent variables requiring real-time optimization. Through the development of digital twins, virtual sensors, computer vision, advanced control, and intelligent decision systems, GreenSIGMA aims to increase energy efficiency, reduce pollutant emissions, and enhance the automation and operational intelligence of WtE plants. The resulting framework will be scalable, adaptable, and aligned with Industry 4.0 and circular economy principles.**

***Index Terms*—Waste-to-Energy, Digital Twin, Advanced Process Control, Artificial Intelligence, Circular Economy.**

I. Introduction

Portugal faces structural challenges in waste management and energy dependence. Currently, more than 50% of national urban waste is deposited in landfills, representing a serious environmental and economic problem. According to AEPSA (Association of Portuguese Companies for the Environment Sector), diverting waste from landfills could imply costs exceeding 800 million euros by 2030 for its adequate treatment [1]. Landfilling contradicts the principles of the circular economy and compromises decarbonization goals. In this context, waste-to-energy (WtE) plants emerge as a strategic solution, by allowing non-recyclable waste to be transformed into energy, reducing landfill disposal, diversifying the national energy matrix, and contributing to the fulfillment of the goals of the National Energy and Climate Plan 2030 and the Roadmap for Carbon Neutrality 2050.

Termogreen is a company specialized in the production of sustainable electricity through the energy valorization of waste, namely forest biomass and, more recently, refuse-derived fuel. With a plant equipped with rotary kiln technology, it has the capacity to valorize up to 35,000 tons of waste per year, which translates into the reduction of about 7,755 tons of CO_2 emissions annually. Despite the initial success of the plant, it was shortly inactive in recent years due to the need to optimize combustion processes to ensure greater efficiency, operational stability, and emission reduction. The process of investment and improvement was gradually completed, revealing in the meantime a reality transversal to the sector: the strong legal pressure, the high operational costs, and the dependence on energy price volatility make the management of these plants extremely demanding.

The scientific foundation for fully optimising these plants remains significantly obsolete. Combustion modelling has progressed via thermodynamic, kinetic, and statistical methods, yet integration with heat transfer models for real-time use remains scarce [2]. Virtual sensors are established in other sectors, but lack adaptive, multi-pollutant estimation capability for WtE [3], [4]. Advanced control strategies often assume fixed dynamics and don't incorporate flame characterisation or virtual sensors, in addition to disregarding market volatility and comprehensive cost-benefit analyses [5], [6]. These limi-

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tations confirm the non-existent of integrated digital solutions for the WtE sector. Operation remains highly dependent on operator experience, constrained by waste variability and environmental pressures, making the new approach proposed in the GreenSIGMA project both timely and essential.

II. The proposed approach

The project will deliver a validated digital platform specifically designed for waste-to-energy plants. Considering the real industrial environment illustrated in Figure 1, the proposed solution incorporates the following innovative components:

1) Operational digital twin of the Termogreen facility with real-time simulation of combustion and heat transfer;
2) Hybrid virtual sensors for continuous estimation of NOx, SOx, and HCL emissions;
3) Intelligent automation observer that monitors PLC logic and PID control cycles;
4) 4D computer-vision system for flame characterisation;
5) Adaptive fuzzy controller that integrates all these data streams;
6) Automatic production-planning system that selects the optimal waste mix based on economic, operational and environmental criteria.

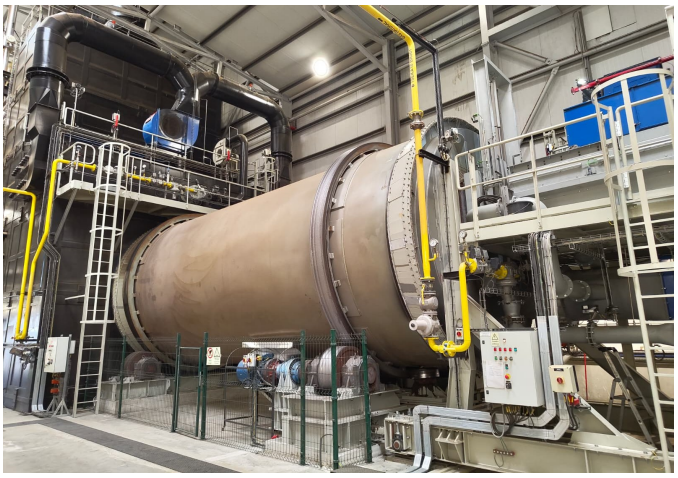

Fig. 1. Overview of Termogreen's industrial plant with a rotary kiln.

This integrated approach is motivated by the current market fragmentation. Existing digital twins are computationally heavy for online use and fail to jointly model combustion, pollutants, and heat transfer. Virtual sensors remain confined to academia with no market application, and automation observers lack reliable detection of logic decision-trees. Crucially, 4D flame characterisation has no academic or commercial precedent, while advanced control and decision tools tailored to waste incineration are virtually absent. To the best of the project authors' knowledge, there is no single solution that simultaneously addresses real-time monitoring, predictive control, and economic optimisation.

III. The Consortium

The consortium brings together five complementary partners. **Termogreen** offers the real plant and operational knowledge of waste incineration, ensuring developments are grounded in operational constraints. **Oncontrol** brings industrial expertise in advanced automation, fuzzy logic control, predictive algorithms, and data analytics, critical for developing the intelligent control backbone. **ADAI** anchors the project's understanding of complex combustion phenomena, heat transfer, and energy generation through its extensive research track record. **University of Coimbra** delivers capabilities in computational modelling, computer vision, virtual sensors, and multi-criteria decision systems, ensuring the underlying algorithms are both scientifically robust and practically applicable. **BIANNA** contributes international experience in thermal engineering and WtE, ensuring the solution is scalable, replicable across different plants, and commercially viable.

IV. Conclusions

The GreenSIGMA project represents advance in digitalization and optimization of WtE plants, addressing gaps through the integrated development of digital twins, virtual sensors, computer vision, advanced control, and intelligent decision systems. Consortium's competencies ensure comprehensive coverage of the scientific and technological challenges. Beyond innovation, the project will reduce technical and operational barriers, increasing competitiveness and contributing to the reduction of waste sent to landfills, with positive impacts on the environment, public health, and well-being. The scalable and adaptable framework, aligned with Industry 4.0 and circular economy principles, positions the consortium at the forefront of innovation and sustainability. Generated knowledge will be transferable to other industrial sectors with complex thermal processes (e.g., cement industry), amplifying project's impact and supporting Portugal's and Europe's energy transition and circular economy objectives.

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