Modelling of a Solar Thermal Energy System for Energy Efficiency Improvement in a Ceramic Plant

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1 Introduction

The industrial sector is responsible for about 25% of the final energy consumption in Europe [1]. Within European industry, such high energy consumption level is mainly due to thermal energy use, accounting for 70% of the total energy use [2]. Thermal energy is primarily generated by the burning of a fuel (such as natural gas) within the operation of a combustion system [3]. The implementation of energy efficiency improvement relies on the application of several measures [4]. One specific set of measures are the one related to heat recovery, this is, the supply of a determinate quantity of heat to enable savings in the primary heat source (fuel) [5]. Another solution is the use of renewable energy resources (such as solar energy) and the implementation of renewable energy systems, which simultaneously reduces the consumption of fossil fuels and indirectly improves the plant's overall energy efficiency [6].

The improvement of energy efficiency and the promotion of renewable energy resource use in the European Union has been secured through several policies. In specific, the 2020 climate & energy package objectives were updated on the most recent 2030 climate & energy package, in which the minimum targets of 32.5% improvement in energy efficiency, 32% share for renewable energy and 40% cuts in greenhouse gas emissions are established [7].

The research on energy efficiency improvement in the industrial sector subsist on several rigorous methods [8]. The application of these methods results on the development of process and system-level models [9]. Numerical modelling may be applied in a multiscale perspective in order to either develop models for single unit operations in a plant or a building or the whole system which encompasses a set of processes. The Modelica language has been used to develop models and study the implementation of several types of measures [9–11]. Several open source libraries have been developed in Modelica for the simulation of several systems. For instance, the modelling of the overall industrial systems encompassing thermal processes and water networks has been secured by the use of the ThermoPower library [12], with its derivative WaterWatt library being specifically used for the modelling of industrial water circuits [9, 13]. On the other hand, the Soltermica [14] and SolarTherm [15] have been used to model and simulate several solar thermal systems [16, 17].

This chapter presents an innovative approach to improve the energy efficiency of a ceramic plant based on the implementation of a system which combines heat recovery and the use of solar thermal energy. Such implementation is studied through the development of a model of the system assembled using the Modelica language. In a broader perspective, this study is inserted in an overall research which encompasses the promotion of energy efficiency in industry (focusing on the optimization of thermal processes) and which in practice is performed by the development of a modelling and simulation tool. This chapter aims to present the modelling approach (equipment and plant-level), validate the tool and demonstrate the associated potential.

2 Materials and Methods

In this section, the description of a case study undertaken in a ceramic industry plant is presented, the aspects regarding the modelling of the plant's components and the conceptualization of the solar thermal energy system (STES).

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Table 1 Technical specifications of the plant and the two boilers

Plant			
Natural gas consumption (GWh/year)	84.47		
Operational time (h/year)	7784		
Boiler 1		**Boiler 2**	
Natural gas consumption (MWh/year)	137.50	Natural gas consumption (MWh/year)	137.50
Water inlet temperature (°C)	25	Water inlet temperature (°C)	25
Water outlet temperature (°C)	95	Water outlet temperature (°C)	95
Water flow rate (kg/h)	1277.38	Water flow rate (kg/h)	1180.32

2.1 *Description of the Case Study*

This case-study is introduced in a ceramic brick manufacturing plant located in Portugal. The production line is constituted by two tunnel kilns, one intermittent kilns, two continuous dryers and four hot water boilers. The plant is located in a zone with high levels of solar irradiation over the year.

Currently, there are already implemented a waste heat recovery strategy in the plant which encompasses the use of the waste heat of the exhaust gas streams of the two kilns to be supplied to brick yards. Nonetheless, currently there is a requirement to optimize the performance of the thermal processes within the plant by reducing the natural gas consumption. Another project (which is also being conceptualized at the same time as the project which is the subject of this chapter) encompasses the use of the waste heat potential of these exhaust gases to be used to heat up the water streams at the inlet of two of the boilers, as well as the recycling of hot air from the cooling zone of one tunnel kiln to be used as preheated combustion air in the firing zone of the same kiln. The present study approaches the optimization of the remaining two boilers. The technical specifications of these boilers are presented in Table 1 (for convenience reasons, these boilers are numbered as boiler 1 and boiler 2).

In this prospect, a new strategy must be defined in order to attend for the described requirement. This study approaches a heat recovery strategy which makes use of solar energy, namely through the installation of solar thermal collectors. The solar thermal energy serves as such as the additional heat source for the operation of the boilers.

2.2 *Modelling of System Components*

The proposed WHR strategy will be studied and assessed through the assembling of a model of the interconnected operations of the plant. The Modelica language is used to model the equipment and simulate the overall operation of the plant. Although a part of the component models necessary to assemble the model of the conceptualized installation are present in existing Modelica libraries (which highly reduces the requirements for model development), some models do not exist in the available libraries (such as the hot water boiler model). As such, some component models had to be assembled to achieve the aims of this research. Two open source Modelica libraries for this prospect: ThermoPower [12] and Soltermica [14]. In Table 2, the libraries used to develop the models presneted in this work are described, with the component models provided by each one of these libraries being identified.

Table 3 presents a brief description of the component models developed from scratch for the aim of this research: the solar collector (modified version of the one from Soltermica) and the boiler.

$$q_{\text{supply}} = M_{\text{fuel,initial}}\text{LHV} \quad (1)$$

$$q_{\text{supply}} = M_{\text{fuel}}\text{LHV} + q_{\text{additional}} \quad (2)$$

$$q_{\text{additional}} = M_{\text{Water}}C_{P,\text{Water}}\left(T_{\text{Water}} - T_{\text{Water,initial}}\right) \quad (3)$$

The total supplied heat in the boiler (q_{supply} (kJ/h)) may be calculated considering the fuel's lower heating value (*LHV*), attending to Eq. (1) (only valid for the case in which there is only one heat source, which is fuel). For the case in which more than one heat source exists to supply thermal energy to the kiln, it is necessary to consider an additional heat parcel as described by Eq. (2), which corresponds to additional thermal energy contained in the inlet water stream ($q_{\text{additional}}$ (kJ/h)), as described by Eq. (3). It is to note the remaining nomenclature used in the set of Eqs. (1), (2), and (3): $M_{\text{fuel, initial}}$ – baseline case fuel mass flow rate (kg/h), M_{fuel} – fuel mass flow rate (kg/h), $M_{\text{Comb. Air}}$ – combustion air flow rate (kg/h), $C_{P,\text{ Comb. Air}}$ – air

Table 2 Description of Modelica libraries used to assemble the STES model

Library	Description	Components
ThermoPower [12]	A Modelica library developed for the dynamic simulation of thermal power plants and energy conversion systems. Although it does not contain models for high-level combustion processes, it contains several basic models which may be used for the assembling of these models (such as combustion chambers, gas flow models and water flow models).	Pipes Tank Pump (modified version) Basic components for the development of the tunnel kiln and boiler models
Soltermica [14]	A Modelica library developed for the simulation of low temperature solar thermal systems, focusing on the design of solar water heating systems. Its focus is on residential buildings.	Solar collector (modified version).

Table 3 Description of newly developed components

Name	Description
Solar thermal collector	It consists of a simplified model for a solar thermal collector. The component model was adapted from the solar collector model of Soltermica. Two connectors from ThermoPower library for, respectively, the inlet and outlet of the water stream were added to this model so to make possible the model to be connected to the components assembled using this library.
Boiler	It consists of a hot water boiler. It is assembled according to the mass and enthalpy balances in an industrial boiler (water stream and combustion chamber), as described in Eqs. (1), (2), and (3). The thermal efficiency (ratio between supplied energy and the variation of the enthalpy of the water stream) is considered in the overall mass-enthalpy balance (thus accounting for the overall heat losses).

heat capacity (kJ/(°C.kg)), M_{Water} – water mass flow rate (kg/h), $C_{P,\text{Water}}$ – water heat capacity (kJ/(°C.kg)), T_{Water} – water inlet temperature at the boiler (°C), $T_{\text{Water, initial}}$ – baseline case water inlet temperature (°C).

2.3 *Modelling of the Solar Thermal Energy System*

The proposed solar thermal energy system (STES) was conceptualized considering the layout presented in the research by Kumar et al. [6]: it overall consists of an industrial water circuit (IWC) constituted by two water flows, one which passes by a solar collector and the other that corresponds to the water that is supplied to the boilers. The STES (this is, the whole installation excluding the boilers) is constituted by the solar collector, a centrifugal pump, a water storage tank and several pipelines. The system is presented in Fig. 1.

The model for the system encompassing the water circuit and the two boilers is presented in Fig. 2. This model was created by using the components identified and described in the previous section.

A set of assumptions were considered in the performance of the whole modelling:

- The air-to-fuel ratio in the boiler is constant, not varying according to different operational conditions.
- The ambient temperature is 25 °C and the ambient pressure is 1 bar.

3 Results and Discussion

In this section, the main results obtained by the simulation of the assembled model are presented and analysed. The section is divided in two subsections, the first one being a presentation of the simulations results and model validation and the second one being a primary technoeconomic assessment performed to evaluate the viability of the implementation of the presented project.

3.1 *Simulation Results and Model Validation*

The assembled plant model was simulated using OpenModelica 1.14.1, an open source distribution of Modelica. The model conceptualized for both components and plants are developed in a basis of dynamic simulation, although the simulation performed for the purpose of model validation was realized in a steady state perspective – the simulation values tend to stabilize at a certain point of the simulation attaining constant values.

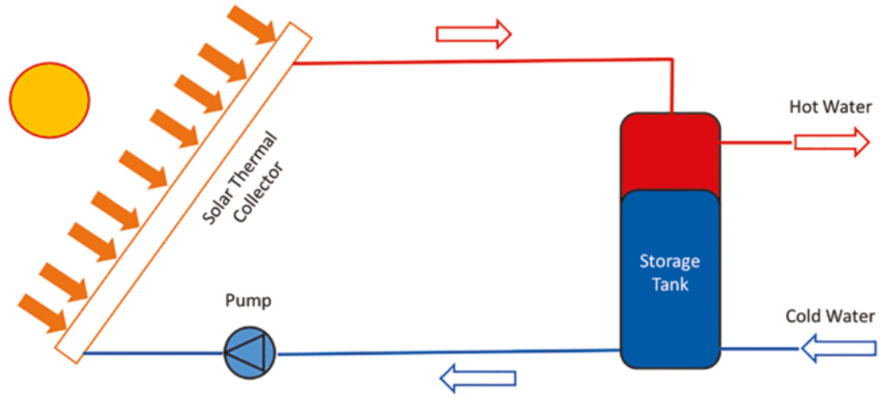

Fig. 1 Flow sheet of a solar thermal energy system including a solar collector and a water storage tank. (Adapted from Kumar et al. [6])

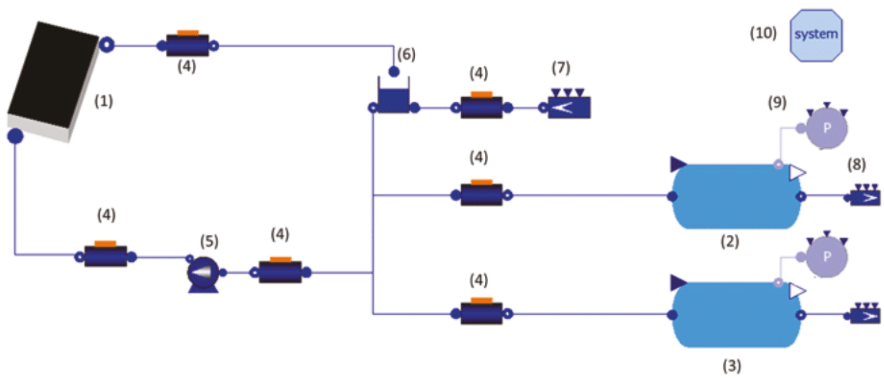

Fig. 2 Assembling of the solar thermal energy system in OpenModelica: (1) Solar collector, (2) Boiler 1, (3) Boiler 2, (4) Pipes, (5) Pump, (6) Water storage tank, (7) Water Source, (8) Water Discharge, (9) Exhaust Gas Discharge, (10) System model

By observing Table 4, the results for the validation of the two boiler models are consistent with real plant measured data. While for the circuit components it is not possible to perform such validation (as it consists of the conceptualized part of the model, not the already existing one), Table 5 presents the outputs of the simulation which serve as the baseline of equipment sizing.

3.2 *Techno-Economic Assessment*

With base on the simulation of the assembled model, it was performed a primary technoeconomic assessment in order to evaluate the viability of the project. This assessment is performed by determining the overall economic savings and calculate the payback time, taking into account an estimative for the investment cost. The economic savings were calculated considering the 2020 price for natural gas and electricity for industrial users (11.64 €/kWh [18] and 0.1654 €/GJ [19], respectively). The investment cost was roughly estimated considering the data present in the technical brief elaborated by the International Renewable Energy Agency (IRENA) and International Energy Agency (IEA)–the Energy Technology Systems Analysis Programme (ETSAP) [20]. Furthermore, a set of assumptions were taken to perform this assessment:

- The economic evaluation overall considers a simple payback, not considering an inflation rate of the investment costs.
- Several investments are considered to be intrinsic to the company, such as the material for repairs and substitution of equipment and the overall maintenance work.

The results for energy and economic savings are presented in Table 6 and the final determination of the payback time is presented in Table 7.

Table 4 Simulation Results and Validation (Boilers)

Component		Variable	Values		Deviation (%)
			Simulation	Real	
Boilers	Boiler 1	Water flow rate (kg/h)	1277.38	1277.38	0.00
		Water outlet temperature (°C)	94.99	95.00	0.01
	Boiler 2	Water flow rate (kg/h)	1180.32	1277.38	0.00
		Water outlet temperature (°C)	94.99	95.00	0.01

Table 5 Simulation results (circuit components)

Component		Variable		Simulation result
Circuit		Water flow rate (kg/h)		5000
		Temperatures (°C)	Before the solar collector	91.68
			After the solar collector	99.68
Pipes	Tank to pump	Inlet pressure (bar)		2.007
		Outlet pressure (bar)		1.989
	Pump to collector	Inlet pressure (bar)		2.057
		Outlet pressure (bar)		2.054
	Collector to tank	Inlet pressure (bar)		2.054
		Outlet pressure (bar)		1.013
	Tank to boiler 1	Inlet pressure (bar)		2.007
		Outlet pressure (bar)		2.006
	Tank to boiler 2	Inlet pressure (bar)		2.007
		Outlet pressure (bar)		2.006
Water storage tank		Inlet pressure (top) (bar)		1.013
		Inlet pressure (base) (bar)		2.007
		Outlet pressure (bar)		2.007
		Water level (m)		10.51
Pump		Inlet pressure (bar)		1.989
		Outlet pressure (bar)		2.057
		Power (kW)		11.65

Table 6 Determination of energy and economic savings

Natural gas consumption				
	Energy consumption		**Energy savings (MWh/year)**	**Boiler economic Savings (1000 €/year)**
	Initial	**Improved**		
Boiler 1	1070.32	390.60	681.72	7.92
Boiler 2	1070.32	218.18	854.14	9.93
Electricity consumption				
	Energy consumption (MWh/year)		**Additional investment (1000 €/year)**	
Pump	90.68		12.43	
Balance				
Boiler economic savings (1000 €/year)	**Additional investment (1000 €/year)**		**Economic savings (1000 €/year)**	
17.85	12.43		5.42	

Table 7 Determination of payback time

Economic savings (1000 €/year)	Total investment cost (€)	Payback time (years)
5.42	57,000	10.52

Regarding the energy balance, it is to note that appreciable economic savings are possibly to be obtained in the case that the economic savings produced by the fuel savings are more significant than the additional investment caused by electricity consumption namely by the circuit pump, which effectively is the case. The economic viability evaluation may be performed by comparing the estimated payback time (10.52 years) with reference values: while for solar water heating projects it may be acceptable (conisdering an acceptable payback time of less than 20 years [21]), comparing with typical energy efficiency improvement projects in the European industry (typical payback time of 2 – 3 years) the conceptualized project may not be economically viable.

4 Conclusion

This chapter presents an innovative framework for the improvement of energy efficiency in the industrial sector, namely through the use of renewable energy resources. This study is included in an overall research which encompasses the promotion of energy efficiency in industry, focusing on the optimization of thermal processes, which uses an innovative modelling and simulation tool developed in Modelica to perform the necessary studies. In this chapter, a case study undertaken in a ceramics plant is analysed and a project to improve the operation of two boilers existing in this plant is assessed.

For the aim of the study, an industrial implementation was projected, consisting of a solar thermal energy systems (STES) for the use of solar energy as an additional heat source in the boilers. The conceptualized system was modelled and simulated, with the main set of results being obtained: the results for the installed boilers (the models were validated and the results were consistent with real plant measured data) and data for the sizing of the water circuit encompassing the solar collector. A primary technoeconomic assessment based on a rough estimate of the investment cost of the installation was performed. An estimated payback time of 10.52 years was determined, considering balanced annual economic savings of 5420 €/year. While the return on investment is acceptable for renewable energy integration project, it far surpasses the acceptable payback time for a heat recovery project. Nonetheless, such project may become economically viable by integrating it within other heat recovery projects which by themselves have low payback times.

As thischapter is based on the validation and potential assessment of the presented modelling tool, it serves as a conceptual basis for the ongoing overall research on thermal process optimization. Future work would then include the dynamic simulation of the conceptualized system and the performance of a life cycle assessment (LCA) of the project.

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