# First step to define a predictive model of the behaviour of a building's thermal system to analyse the climate change influence


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**Abstract:**

Buildings account for 40% of the EU's final energy consumption and 36% of its energy-related GHG emissions. Therefore, to reduce the EU's GHG emissions it is needed to reduce the energy consumption and increase energy efficiency. For that, not only the design but also the maintenance of systems is essential to ensure the proper functioning and the energy efficiency. On the other hand, the environmental temperature is rising at a high rate because of the global warming. Therefore, this will undoubtedly influence on the energy efficiency of the buildings thermal systems. However, we can only estimate the effects from predictions based on previous data models.

In this work we develop a methodology in order to learn a predictive model of a simple thermal system of a building, consisting of a boiler and the distribution equipment that provides the dynamic DHW demand. The model is learn from databases obtained from a thermal system software to calculate the influence of climate change on the cost formation process. That is, we quantify the effects on costs due to outdoor temperature variation when the demand does not vary, based on thermoeconomic indices. The next step will be to incorporate heating demand that will also vary due to climate change.

The reference model of the thermal facility would serve to predict the behaviour when the climate changes, in order to implement it in maintenance tasks and thermoeconomic diagnosis for fault detection.



**Keywords:**

Predictive model; Thermal installation; Buildings; Climate-change.


## 1. Introduction

Buildings account for 40% of the EU's final energy consumption and 36% of its energy-related greenhouse gas (GHG) emissions. Therefore, reducing energy consumption and increasing energy efficiency are required to reduce the EU's GHG emissions [1].

On the other hand, due to climate change, environmental temperature is rising at a rapid pace. The global average temperature has risen by 0.76°C over the last 100 years [2] and, in addition, global average warming is estimated to be 2.2°C by 2100, 3.6°C by 2200 and 4.6°C by 2500, with all the consequences that this entails [3]. After all, buildings must generate thermal comfort and meet energy needs according to the variable external conditions and the profile of the users.

The research of predictive behavioural models to improve continuously the building installations and their maintenance is a key point to ensure the intelligent operation of equipment and to detect premature wear of engines. With predictive models learned from simulated thermal data, it is possible to set a competitive regime and timing of processes, to detect excess energy consumption, or to detect malfunctions.

For all these reasons, the key for a proper management and energy savings lies, among others, in predicting the operation of systems and the cost of the products required in the future, to (1) be able to take the necessary actions to adapt to new climatic conditions, and, to (2) slow down the increase in the Earth's surface temperatures, reducing GHG emissions. Thus, one of the keys to guarantee the proper functioning of thermal systems in buildings and to promote the energy efficiency are maintenance actions.

A survey of the state of the art of work applying thermoeconomics in combination with AI shows that there are some recent studies. The work in [4] creates a model that applies the principles of thermoeconomics to analyse

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and optimize the performance of the Afyon geothermal power plant. This modelling approach is enhanced by using artificial neural networks to improve the plant's efficiency and cost-effectiveness. In Ref. [5] the thermoeconomics aspects of a system that combines geothermal and solar energy to produce both hydrogen and power are studied. This analysis involves using advanced techniques such as artificial neural networks and genetic algorithms to optimize the system's performance. In the work in [6] artificial intelligence and response surface methods are used in order to optimize the thermoeconomic performance of waste heat recovery system in a large internal combustion engine.

As shown in the literature, the studies are focused on the application of Thermoeconomics and Machine learning methods for optimising industrial systems. In this way, this study provides a methodology that combines both disciplines for maintenance work in building thermal systems.

Therefore, this paper presents a case study of a dynamic thermoeconomic analysis applied to a domestic hot water (DHW) installation and develops a methodology to create a model, which aims to predict the performance and the costs and consumption of thermal systems in buildings, for their maintenance. This model combines Thermoeconomics with data-driven Machine Learning (ML) methods. Data-driven methods extract patterns from historical process data [7], which are very useful for monitoring and model building thermal systems due to the large amount of data collected and the dynamic operation.

## 2. Materials and methods

This section explains the laboratory where the system has been designed, the thermoeconomics applied to the study as well as the thermoeconomics and TRNSYS software needed to carry out the case study.

### 2.1 Building Quality Control Laboratory of the Basque Government

The Building Quality Control Laboratory of the Basque Government (LCCE) is a laboratory prepared to carry out physical, mechanical and chemical tests on construction materials. It is divided into three areas: thermal, acoustic and materials. Thus, the thermal area has a flexible experimental plant designed to configure different installations depending on the required demand. For this purpose, the installation can be divided into different zones or islands, as can be seen in Figure 1: (1) low temperature zone, (2) high temperature zone and (3) solar collector zone. These three zones correspond to the different generation equipment. There are also (4) the distribution equipment zone, (5) the heating/DHW terminal zone and finally (6) the thermal storage zone.

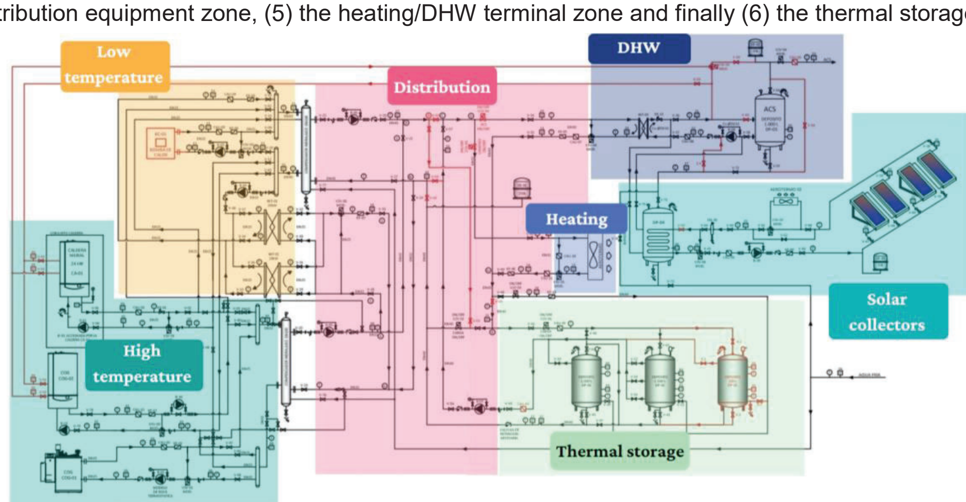


**Figure 1**. Experimental plant of the LCCE

The installation consists of more than 100 signals to control and monitor the variables to be evaluated. For this, 46 high precision Pt 100 class 1/10 temperature probes are used, 40 of them located in pipes and the rest in tanks, 11 SIEMENS FM electromagnetic flowmeters (MAG 3100 and 5100W sensors and MAG 6000 transmitters), 2 pressure switches, one in the general circuit and the other in the solar circuit. It also has ambient temperature, humidity and pressure sensors both inside and outside the laboratory. The boiler and the micro-cogeneration equipment have gas and electricity meters and the consumption of the heat pump is also monitored.

The entire control of the installation is managed by a Siemens IM 151-8 PN/DP CPU for ET200S and an expansion module, as well as the corresponding input and output cards for the signals, connected via Ethernet to a PC where the interface is available through which the operation is carried out and the data are collected.

### 2.2 TRNSYS

TRNSYS [8] is a flexible software environment for simulating the behaviour of transient thermal systems in buildings, composed of two parts:

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- The first is an engine (called the kernel) that reads and processes the input file, iteratively solves the system, determines convergence and plots system variables. The core also provides utilities that determine thermophysical properties, invert matrices, perform linear regressions, interpolate external data files, etc.
- The second part consists of an extensive library of components, each of which models the performance of a part of the system. The standard library includes approximately 150 models ranging from pumps to multi-zone buildings, from wind turbines to electrolysers, from weather data processors to economics routines, and from basic HVAC equipment to the most advanced emerging technologies. The models are built in such a way that users can modify existing components or write their own, extending the capabilities of the environment.

Accordingly, TRNSYS version 18 has been used for this simulation.

## 2.3 THERMOECONOMICS

The Exergy Cost Theory is based on a series of Propositions, whose systematic application makes possible to unequivocally determine the value of the costs (in energy and monetary units) of each of the flows of the system under analysis [9].

The previous step for applying thermoeconomic analysis is to determine the *physical structure*, where all material and energy flows are represented. Furthermore, the approach of the structural theory of thermoeconomics goes beyond the physical structure of the system and defines its *productive structure* in a matrix form. In order to carry out a productive analysis, the flows are classified according to the function they perform in the equipment. This representation considers each equipment *i* as a black box with an input arrow, called fuel ($F_i\ [kWh]$), and an output arrow, product ($P_i\ [kWh]$). The $F_i$ of a component *i* represents the resources (measured in exergy terms) needed to run the specific energy process and $P_i$ contains the target of the process itself. Therefore, the difference between both terms represents the irreversibility of the process ($I_i = F_i - P_i$) and the ratio $\left(k_i = \frac{F_i}{P_i}\left[\frac{kWh}{kWh}\right]\right)$ reflects the unit exergy consumption of the component, which expresses the amount of fuel required to generate one unit of product. This coefficient is related to the other components through the specific $\mathbf{F}$ and $\mathbf{P}$ interrelationships, given by a matrix $\langle\mathbf{KP}\rangle$, which reflects the productive structure of the system. Likewise, a product of one component can be part of the fuel of another component, or also part of the final product, $\mathbf{P_s}$.

Consequently, the vector $\mathbf{P}$ and $\mathbf{F}$ containing the product and fuel of each team can respectively be calculated by means of the following equations [10]:

$$\mathbf{P} = \mathbf{P_s} + \langle\mathbf{KP}\rangle \cdot \mathbf{P} \tag{1}$$

$$\mathbf{F} = \mathbf{I} + \mathbf{P} = \mathbf{K_D} \cdot \mathbf{P} \tag{2}$$

where the final product vector is $\mathbf{P_s}$; $\mathbf{K_D}$ is a diagonal matrix containing the total unit exergy consumption of the components; $\mathbf{I}$ corresponds to the irreversibility vector, and the matrix $\langle\mathbf{KP}\rangle$ reflects, as mentioned before, the productive structure.

Similarly, the total fuel consumption of the system is calculated as follows:

$$F_T = I_T + P_T = \mathbf{k_e} \cdot \mathbf{P} \tag{3}$$

where $I_T$ and $P_T$ are the total irreseversibilities and the final product of the system respectively and $\mathbf{k_e}$ the consumption of external resources.

In relation to costs, the exergy cost $B_i^*\ [kWh]$ expresses the amount of resources used to obtain a specific flow $B_i$, and the unit exergy cost $k_i^*\ \left[\frac{kWh}{kWh}\right]$ expresses the ratio between the exergy cost and its exergy [11]:

$$k_i^* = \frac{B_i^*}{B_i} \tag{4}$$

Furthermore, $k_i^*$ takes into account the resources needed to generate the flow *i* in the energy chain. It increases as the irreversibilities along the chain increase. The unit exergy costs of the equipment products $\left(\mathbf{k_P^*}\ \left[\frac{kWh}{kWh}\right]\right)$ are related to the unit exergy costs of the external resources $k_{e,i}^*$ of component *i* and to the marginal exergy consumption associated with the external resources $k_{e,i}$.

In addition, the exergoeconomic cost of *i* -flow $c_i$ represents the economic resources required to obtain it. The economic costs of internal flows and final products depend on the thermodynamic efficiencies of the processes.

To calculate the exergoeconomic costs of fuels and products, fixed costs and variable costs have to be defined. Variable costs depend directly on the level of production, while fixed costs are the investment, maintenance and operating costs of the equipment, which are represented by the vector $\mathbf{Z}$ [€]. Because of space reasons, this paper defines only the variable costs for the exergoeconomic ones. Therefore, the exergoeconomic unit costs $c_{F,i},\ c_{P,i}\ \left[\frac{€}{kWh}\right]$ represent the unit cost of a given flow, either fuel or product.

To calculate the total cost of fuels and products, the unit exergoeconomic costs are multiplied by their exergy values:

$$C_{F,i} = c_{F,i} \cdot F_i \quad (5)$$

$$C_{P,i} = c_{P,i} \cdot P_i \quad (6)$$

### 2.4 THERMOECONOMICS SOFTWARE

In order to carry out this work, a software to control and diagnosis of thermal installations [12] has been used, which is based on Thermoeconomics. This software combines Matlab [13], where the calculations are performed, with Excel, where the data are recorded and the results are presented.

The software calculates the thermoeconomic costs of each of the flows of the installation, and detects the equipment with the highest irreversibilities, which are the ones that increase the cost the most along the energy chain. The costs are obtained from the productive structure that interconnects all the equipment according to (1) the distribution ratios $b_{ij}$, (2) the unit exergy consumption of each equipment $k_i$, and (3) the external resources $F_{e,i}$.

The software is able to make these calculations in a dynamic way, i.e. for a series of time stamps, so the results obtained are useful for future diagnosis analyses, given that when a parameter of an equipment varies, its unit exergy consumption varies; thus, the costs related to that component also change.

## 3. Case study

This work develops the previous steps to build a predictive model of a DHW installation based on the influence of climate change.

For this purpose, a simple DHW installation has been simulated in TRNSYS software emulating the installation designed in the LCCE´s experimental plant, since the final objective is to create the predictive model of real thermal facilities.

With the simulation data, thermoeconomic variables have been calculated for each instant of time, i.e. dynamic variables, such as the total cost of the installation product and, finally, the predictive model has been developed to predict the future values of these costs based on changes in the external temperature.

### 3.1 Design of the installation

As case study, the installation has been designed to produce DHW using a 24 kW gas boiler, as shown in Figure 2, for a residential building with 20 inhabitants in Vitoria-Gasteiz.

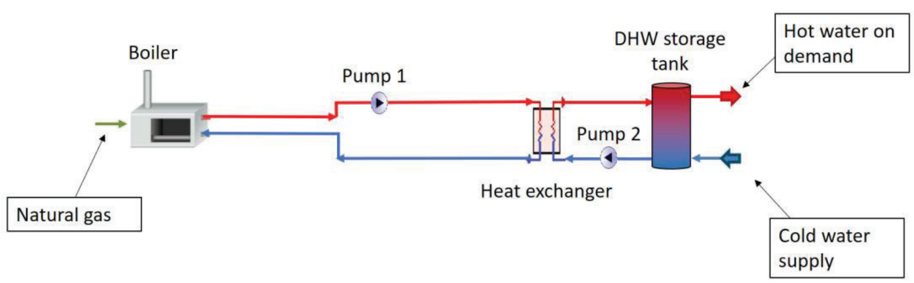


**Figure 2.** Installation diagram

The installation consists of:

- Generation: 24 [kW] gas boiler.
- Distribution: Hydraulic pumps, heat exchanger.
- Storage: DHW tank of 100 [l].

The parameters of the components are the ones of the LCCE´s experimental plant.

### 3.2 Physical configuration and productive structure

Once the installation has been designed, the physical configuration and the productive structure are determined to carry out a subsequent thermoeconomic analysis. To define the physical configuration, all material and energy flows are represented. Thus, as shown in Figure 3, 9 flows are defined:

- Energy consumption flow: 1.
- Mass flows: 2, 3, 4, 5, 8, 9.
- Virtual inertia flows: 6, 7, which represent the temperature charge and discharge of the tank.


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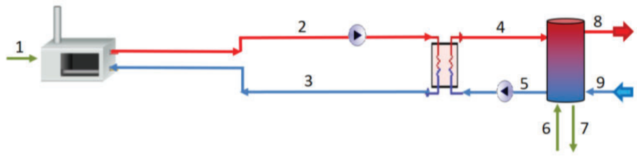

**Figure 3.** Physical configuration of the installation

In the productive structure, the components are defined as black boxes with interconnected input fuels and output products. In addition, virtual equipment (the green equipment in Figure 4) is added.

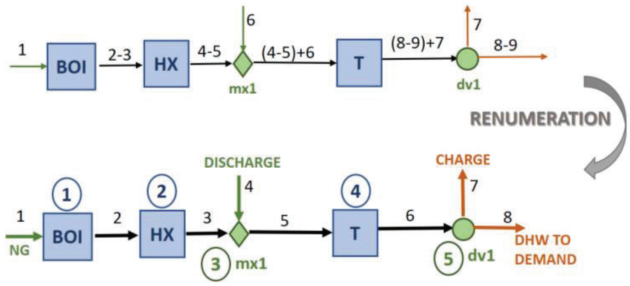


**Figure 4.** Productive structure of the installation

After renumbering the flows, for simplicity reasons, we have a total of 8 flows and 5 equipment: (1) BOI-boiler, (2) HX-heat-exchanger, (3) mx1-mixer 1, (4) T-tank and (5) dv1-diverter 1.

## 3.3 Modelling in TRNSYS

The designed installation has been modelled in TRNSYS software maintaining the parameters of the LCCE equipment (Figure 5).

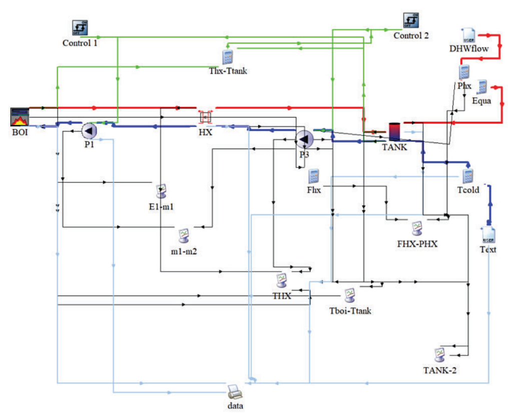


**Figure 5.** Simulation Studio interface in TRNSYS of the installation

### 3.3.1 Calculation of the DHW demand

The demand profile has been calculated according to the parameters set out in the HE4 of the CTE (Spanish Technical Code [14]) for a residential building with 20 inhabitants.

### 3.3.2 Implementation of the outdoor temperature

The main objective of this work is to predict the behaviour and the change in cost of the total product of the installation in future periods, when the outdoor temperature varies.

It is needed to take into account that, in order to achieve this, we have taken into account that the outdoor temperature and the cold water supply temperature are related. In this way, the temperature of the cold water supply entering the system can be calculated as a function of the outdoor temperature, which is used as a predictor variable we are going to use in the model.

Therefore, the average monthly values of the external temperatures in Vitoria-Gasteiz from the IDAE (Institute for Energy Diversification and Saving) [15] and the average monthly temperatures of the mains water in Vitoria-Gasteiz from the Spanish CTE were taken [14].

The relationship with the highest Pearson correlation (R) between these two variables is the linear one below with R=0.9795:

$$T_{cold\ water} = 0.6526 \cdot T_{ext} + 3.3462 \tag{7}$$

Thus, the cold water supply temperature is calculated for all outdoor temperatures according to the LCCE's outdoor temperature sensor.

#### 3.3.3 Control configuration

The control has been configured as follows:

- The boiler starts when the domestic hot water storage tank is below 60.5ºC and stops when it exceeds 62ºC.
- The DHW production starts when the temperature at the primary inlet of the heat exchanger is 5ºC higher than the tank temperature and stops when it is less than 2ºC.

#### 3.3.4 TRNSYS data

TRNSYS allows downloading an Excel file with the thermodynamic variables necessary for subsequent analysis. Specifically, each time-step it saves the following values:

- Temperatures of each flow and average temperatures of the hydraulic compensator and tank.
- Flow rates of each flow.
- Boiler fuel consumption.

The selected data coincide with the data that can be extracted from the LCCE installation and are sufficient to calculate the energy and exergy values for each flow of the productive structure as will be done later, during 168 [h] with 1-minute time-step.

### 3.4 Data analysis and pre-processing

From the extracted data, a "*raw database*" is obtained based on the dynamic data of temperatures, flow rates and consumption. They are used to calculate, once processed, the energies of each flow. These variables are the same as those that could be obtained from sensors installed in the LCCE.

First, in order to clean and pre-process raw data, the data are visualised to check for outliers that do not follow the normal pattern of the data series. In addition, some conditions are established to avoid intrinsic failures of TRNSYS when extracting the data.

With the pre-processed data, the corresponding energy flows in and out of each main equipment are calculated, based on the First Law of Thermodynamics, and the dynamic model is defined. Thus, an "*energy database*" is obtained that provides the global vision of the interconnections between the components.

### 3.5 Analysis of the active operating modes of the plant

The casuistry of the installation's behaviour is analysed on the basis of the productive structure, i.e. the active operating mode is identified at each moment, see Figure 6:

- 1st casuistry: Tank charge

The tank is below the temperature set in the control (60.5ºC), so there is a generation demand on the boiler that loads the tank.

- 2nd casuistry: Tank charge + demand

DHW demand exists and the tank is below the temperature set in the control (60.5ºC), so there are two products: tank charging and demand for DHW consumption.

- 3rd casuistry: Demand with tank discharge

DHW demand exists and the tank is above the temperature set in the control (62ºC), so the tank discharges.

- 4th casuistry: Demand without tank discharge

DHW demand exists and the tank is above the temperature set in the control (62ºC), but it does not discharge. This is physically impossible, as if there is a DHW demand, the tank must discharge, i.e. the temperature in the tank must be reduced. However, this casuistry does not cause any problem when carrying out the thermoeconomic analysis, as explained in the following section *3.6. Thermoeconomic analysis*.


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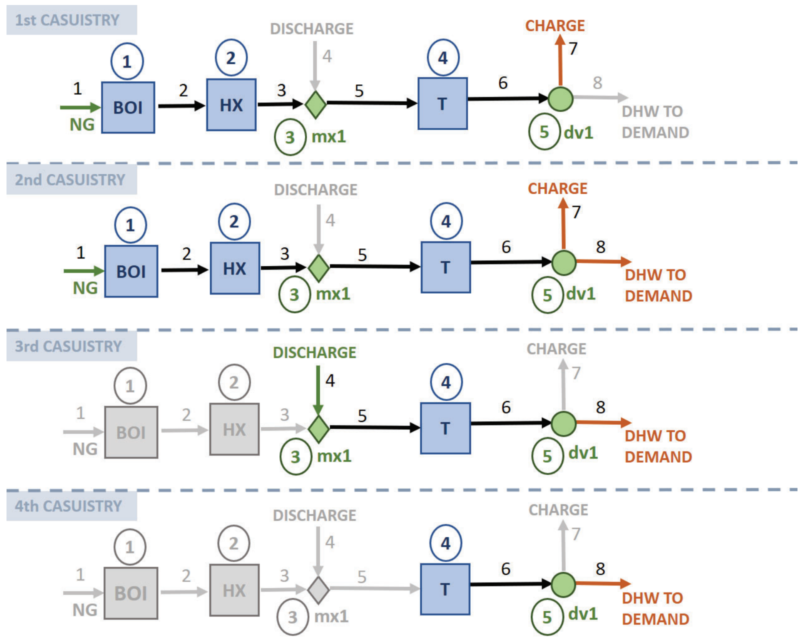


**Figure 6.** Casuistry of the behaviour of the installation

After analysing the operation modes, it is foreseen that in the 3rd casuistry, there is no natural gas consumption, as the boiler is off. Nevertheless, the discharge of the tank happens because in previous operation modes, gas is consumed to charge the tank. So, in order to consider the cost of charging-discharging the tank, a new methodology is developed to disregard this 3rd casuistry.

To understand the methodology, it is necessary to understand the tanks' energy-exchange formula:

$$\Delta E\ [kJ] = V_{tank}[l] \cdot \rho_w \left[\frac{kg}{l}\right] \cdot Cp_w \left[\frac{kJ}{kg \cdot K}\right] \cdot (T_{t-1} - T_t)[K] \tag{8}$$

To equal the $\Delta E$ value to 0, the tank temperature at the previous instant $T_{t-1}$ needs to be equal to the tank temperature at the current instant, $Tt$.

Therefore, we only consider the $\Delta t$ instants in which the tank temperature is equal to $T_t = T_{t-1} = 60.5$°C, as this is the lower temperature fixed in the control. Afterwards, we recalculate the corresponding $\Delta t$ instants and energy flows in a "*new energy database*" consists of 215 lines of data, which is a 98% reduction of data lines compared to the previous data sheet extracted from TRNSYS. By means of this methodology not only the 3rd casuistry is disregarded, but also the computational burden for the thermoeconomic analysis is notably reduced.

### 3.6 Thermoeconomic analysis

In order to carry out the thermoeconomic analysis, the following steps are followed:

1. Calculation of the "*exergy database*": the exergy flows corresponding to all flows are calculated based on the First and Second Laws of Thermodynamics.
2. Definition of economic values: the price of natural gas is defined as the only external resource, without considering the net water price.
3. Calculation of the thermoeconomic values by means of the thermoeconomics software for the following results:
   - Unit energy consumption of the *n* equipment: $k_n$
   - Unit exergy costs of fuels and products: $k^*_{F_n}$, $k^*_{P_n}$
   - Unit exergoeconomic costs of fuels and products: $c_{F_n}, c_{P_n}$

With the unit exergoeconomic costs of the products, we calculate the total cost of the installation total product $C_{p_{DHW}}$[€], which in this case is the DHW to demand.

### 3.7 Development of the predictive model

This study compares the $C_{p_{DHW}}$[€] cost of the installation in a reference situation (calculated in this work) with the cost in a climate change condition (with an increase in the outdoor temperature). In this way, we calculate the change in the overall consumption of the system as well as the increase in the individual components $\Delta k_n$, that will indicate the effects generated by that change.

Therefore, it is needed to quantify how the outdoor temperature variable is related to the intermediate costs of the system. Therefore, the costs are modelled according to the following options:

1. Each variable to be predicted (the intermediate costs as a function of outdoor temperature) can be modelled independently, from known temperature data.
2. A stepwise process can be carried out in which, once variables are predicted, they are incorporated as predictors to infer the missing ones.
3. All variables can be predicted at once.

These three points can be implemented in two ways:

- Taking into account information from previous instants to predict the current instant. RNN (Recurrent Neural Networks) methods attempt to identify and exploit sequential information in the data. These methods retain in "memory" the information from consecutive components of the sequence. The logic is based on answering the question, "Can the information observed at the instants before the sequence be relevant to predict what happens at the current instant?" If the answer is “yes”, as is the case with time series, then the model tries to detect it and use it to predict variables.
- Considering each moment in time as an independent observation (i.e. ignoring time dependence). This can be applied if the observations of time instants are considered as independent observations; thus, any time dependence relationship between the samples is broken. In this case, other simpler models that do not take into account this temporal dependency, e.g. multi-layer perceptron, are an efficient modelling alternative.

Combining the data-driven application and thermoeconomic concepts, the effect of the change in cost due to a change in external temperature will be quantified.

# 4. Results and discussions

This section explains the obtained results.

## 4.1 Verification of the control

Figure 7 is used to check the control designed for the installation, where 2 days out of the 7 days of the test were depicted. These graphs also demonstrate the dynamism of the installation, with the following conclusions:

- On the one hand, Figure 7a shows that when the temperature difference between the primary heat exchanger inlet and the tank temperature is greater than 5ºC, DHW production starts and stops when it is below 2ºC.
- On the other hand, Figure 7b shows how the boiler starts up when the tank temperature is below 60.5ºC and stops when it is higher than 62ºC.

In other words, the control is correctly designed.

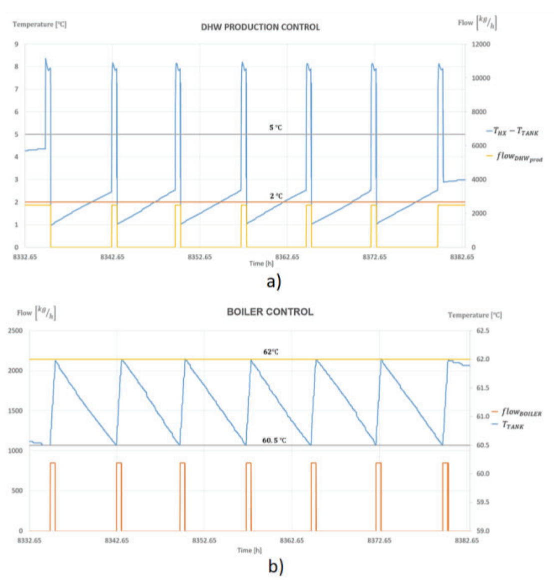


**Figure 7.** DHW production and boiler control verification graphs

## 4.2 Thermoeconomic results

Figure 8 shows the dynamic energy and exergy values of the fuel and boiler product.


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- The exergy values for fuel are higher than the energy values because natural gas has a quality factor $QF_{NG} = 1.04 \left[\frac{kWh_{en}}{kWh_{ex}}\right]$
- However, exergy values of the product are lower than the energy values. This is because the exergy takes into account the quality of the energy flow, which in the case of the boiler is thermal energy. Average values show that the boiler has an energy efficiency of 89.26% compared to the exergy efficiency of 15.58%.

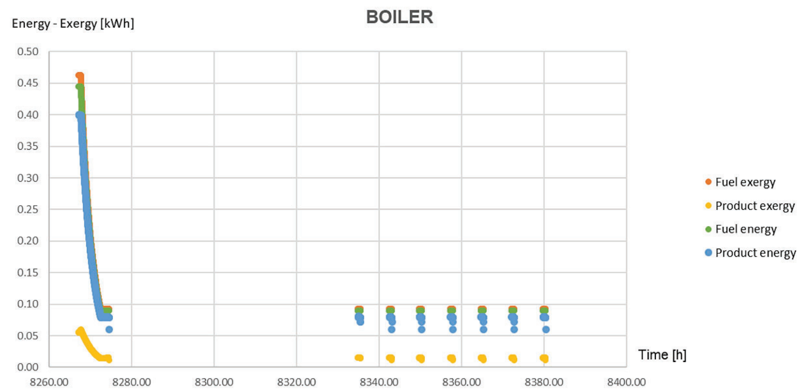


**Figure 8.** Energy and exergy values of fuel and boiler product

Despite having the dynamic values of the thermoeconomic results, due to space limitations, the following results show either the average values or the total sum of the values at each instant. Table 1 shows the total sums of fuels, products and equipment irreversibilities.

- On the one hand, as the energy chain progresses, the exergy values of the flows decrease. This is due to the accumulation of irreversibilities of the equipment.
- On the other hand, the equipment with the highest irreversibilities is the boiler, $I_{boiler} = 19.80\ [kWh_{ex}]$. This is due to the use of a fuel with a high exergy level (natural gas) to generate a product with a lower exergy level (hot water), in addition to the unavoidable exergy destruction intrinsic to the boiler.

**Table 1.** Fuel, product and irreversibilities of equipment

| | EQUIPMENT | $F_{ex}\ [kWh_{ex}]$ | $P_{ex}\ [kWh_{ex}]$ | $I\ [kWh_{ex}]$ |
|---|---|---|---|---|
| GENERATION | BOI | 23.48 | 3.68 | 19.80 |
| DISTRIBUTION | HX | 3.68 | 2.16 | 1.52 |
| PRODUCT | T | 2.16 | 0.29 | 1.87 |

Table 2 shows the average values of the unit exergy consumptions of the equipment and the average values of the unit exergy costs of the fuels and products of each equipment.

- On the one hand, the unit exergy consumption of the equipment, $k_n \left[\frac{kWh_{ex}}{kWh_{ex}}\right]$, represents the amount of fuel required to produce one unit of product, showing that the equipment with the highest unit exergy consumption is the tank, $k_{TANK} = 8.87 \frac{kWh_{ex}}{kWh_{ex}}$. This is due to the mixing of flows at very different temperatures.
- On the other hand, the unit exergy costs of the fuels $k^*_{F,i}$ of the generating equipment, (i.e. the boiler), $k^*_{F,BOILER}$ have the value of 1, since it is an external input flow. It is also observed that the ratio between the unit exergy costs of the fuels and the products of the equipment is proportional to the irreversibilities that occur.

**Table 2.** Unit exergy consumption of equipment and unit exergy costs of fuels and products

| | EQUIPMENT | $k \left[\frac{kWh_{ex}}{kWh_{ex}}\right]$ | $k^*_F \left[\frac{kWh_{ex}}{kWh_{ex}}\right]$ | $k^*_P \left[\frac{kWh_{ex}}{kWh_{ex}}\right]$ |
|---|---|---|---|---|
| GENERATION | BOI | 6.41 | 1 | 6.41 |
| DISTRIBUTION | HX | 1.71 | 6.41 | 10.96 |
| PRODUCT | T | 8.87 | 10.96 | 96.12 |

Table 3 shows the average values of the exergoeconomic costs of the fuels and products of the system's equipment. For this analysis, only the exergoeconomic costs related to variable costs have been calculated, i.e. those that depend on the natural gas consumption.

- The exergoeconomic costs of fuels, $c_F$, take into account the irreversibilities accumulated up to that point in the energy chain; thus, moving down the energy chain, these costs increase.

- The exergoeconomic costs of the products, $c_P$, follow the same trend, as unit exergy costs, and increase when moving down the energy chain.

**Table 3.** Exergoeconomic costs of equipment fuels and products

| | EQUIPMENT | $c_F\ \left[\frac{c€}{kWh_{ex}}\right]$ | $c_P\ \left[\frac{c€}{kWh_{ex}}\right]$ |
|---|---|---|---|
| GENERATION | BOI | 5.07 | 32.52 |
| DISTRIBUTION | HX | 32.52 | 55.57 |
| PRODUCT | T | 55.57 | 487.43 |

The total cost of the DHW for the period studied is $C_P = 285.78\ \frac{€}{7\ days}$.

### 4.3 Predictive model results

The Predictive model itself is not presented in this manuscript. Since we are now working in it, a coming work will contain the corresponding results

## 5. Conclusions

In this work a dynamic thermoeconomic analysis of a thermal installation of a building that produces DHW has been carried out and a methodology to predict the costs of the flows has been shown. This installation is designed based on the configuration of the LCCE's experimental plant and was simulated in the TRNSYS software.

During the thermoeconomic analysis, all the possible operating modes of the case study are analysed, with the following relevant conclusions:

- The equipment with the highest system irreversibilities is the boiler, $I_{boiler} = 19.80\ [kWh]$
- The equipment with the highest unit exergy consumption is the tank, $k_{TANK} = 8.87\frac{kWh_{ex}}{kWh_{ex}}$.
- The total product cost of the installation is $C_{P,DHW} = 287.78\left[\frac{€}{7\ days}\right]$

In addition, the first steps to develop an innovative methodology that combines Thermoeconomics and Machine Learning models is defined, in order to quantify the effects of climate change on the costs and consumption of thermal installations in buildings. This will help promoting maintenance work, which is essential for the proper functioning and for reducing GHGs.

### 5.1 Future lines

As said, we are working on this case study in order to develop the predictive model able to predict both the operation and the consumption and costs based on ML techniques.

Likewise, the fixed costs related to the operation, maintenance and amortisation costs of the installation will also be incorporated in the results.

The next step deals with the implementation in real systems.

In short, work will continue on a tool that combines Thermoeconomics and Machine Learning capable of predicting possible failures in thermal installations of buildings and optimising their operation.

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## 7. Nomenclature

**Symbols**

$B$: Exergy, $kWh$

$c$: Exergoeconomic unit cost, $\frac{€}{kWh}$

$C$: Total cost, €

$c_P$: Specific heat capacity, $\frac{J}{kg \cdot K}$

$E$: Energy, $kWh$

$F$: Fuel, $kWh$

$\mathbf{F}$: Fuel vector

$I$: Irreversibility, $kWh$


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$\mathbf{I}$: Irreversibility vector

$k$: Unit exergy consumption, $\frac{kWh}{kWh}$

$\mathbf{k_e}$: External resources vector

$\mathbf{K_D}$: Diagonal matrix containing the unit exergy consumptions

$\langle\mathbf{KP}\rangle$: Productive structure matrix

$P$: Product, $kWh$

$\mathbf{P}$: Product vector

$T$: Temperature, $K$

$V$: Volume, $m^3$

$\mathbf{Z}$: Depreciation, maintenance and operation vector, €

**Greek symbols**

$\Delta$: Difference

$\rho$: Density, $\frac{kg}{m^3}$

**Subscripts**

$e$: External resource

$ext$: External, outdoor

$F$: Fuel

$i/j$: Generic equipment

$NG$: Natural gas

$P$: Product

$s$: Final product

$t$: Time

$w$: Water

**Superscripts**

$*$ **:** Cost

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