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TdT: A tool for building thermal systems analysis and comparison

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ABSTRACT

This work describes the tool "Towards Dynamic Thermoeconomics" (TdT), which has been designed to analyse the thermal systems of buildings from a dynamic point of view for further thermoeconomic analysis, since HVAC systems consume a significant part of the global energy and have a significant environmental impact. TdT is presented as a versatile, open-source application developed in Python, which provides dynamic energy and exergy performances of components, as well as the most vulnerable points in the system to be optimised. As a novelty TdT introduces a new methodology for analysing inertial systems that defines non-periodic time intervals in which the tank temperature is $T_{tank,rep}$, thus avoiding misleading cost results. Two case studies are presented as examples of typical applications: a domestic hot water system and a heating system, analysed with TdT in eight different climatic locations in Spain. The corresponding results are extracted and analysed, with a particular focus on the influence of the outdoor temperature (T_0) on both the exergy and energy efficiency of the components, the identification of irreversibilities and the total exergy consumption. It becomes evident that as the T_0 increases by 38 %, the exergy efficiency of the boiler decreases in both systems, with an average yearly exergy efficiency decrease of 1.4 % on the DHW system. Furthermore, the boiler is the component with the highest irreversibilities, followed by the inertial and distribution components, information that could not be obtained from energy analysis. Ultimately, the TdT provides valuable insights and a novel methodology for analysing inertial components, which will improve the efficiency and sustainability of building thermal systems.

1. Introduction

The thermal systems of buildings interact with their environment, consuming external resources and transforming them into useful products, such as the energy required to ensure indoor comfort for heating, cooling, ventilation, domestic hot water (DHW), etc. In Spain, this consumption represents 20 % of the final energy consumption, a percentage that is increasing [1]. Moreover, according to Directive 2012/27/EU [2] on energy efficiency, buildings account for 40 % of the total energy consumption in the European Union and, according to the study by L. Pérez-Lombard et al. [3], heating, ventilation and air conditioning systems (HVAC systems) represent almost half of the energy consumed in buildings and around 10–20 % of the total energy consumption. This has a significant impact on available resources and emits polluting gases into the atmosphere. In addition, it is a well-known fact that certain natural resources are rapidly depleted because they do not have time to recover.

In this context, the increasing need for natural resources for energy conversion technologies and their environmental impact,

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among other sciences, led to the development of Thermoeconomics. This is the discipline that combines physics and economics through the Second Law of Thermodynamics in order to save natural resources [4]. It aims to improve the design of energy systems, to reduce environmental damage and is helpful for the maintenance of systems. After all, it is crucial to maintain the thermal systems in buildings to ensure the correct operation of components and to promote energy efficiency. Proper maintenance guarantees the performance of services and serves to establish a preventive approach based on knowledge.

Furthermore, it is important to understand that the behaviour of thermal systems in buildings is highly dynamic, as external environmental conditions, user demand profiles and component failures result in constant changes to the performance of these systems. It is therefore essential to analyse these systems dynamically and collect data continuously in order to obtain an accurate diagnosis in real-time.

Accordingly, this paper presents "Towards Dynamic Thermoeconomics" (TdT), a versatile and freely available tool that addresses the need for dynamic thermoeconomic analysis in the field of thermal systems of buildings. It improves the ability to detect and correct faults in real-time, with a particular emphasis on methodology for the analysis of inertial systems.

In the field of thermoeconomic analysis and diagnostics, several tools are available, including TaesLab [5] and its predecessor, the TAESS application [6], both developed in MATLAB [7]; as well as the software presented by Picallo et al. [8] that combines MATLAB and Excel [9] for dynamic thermoeconomic analysis. These applications are in accordance with the guidelines established by Torres et al. [10] who developed thermoeconomic analysis software. It is important to note that the aforementioned applications have served as the basis for the creation of "Towards Dynamic Thermoeconomics". This indicates that TdT fulfils an indispensable function by bridging the gap between the facility data and specialized free-license applications for thermoeconomic analysis and diagnosis, as the thermodynamic data of each flow is required in order to perform any energy and thermoeconomic analysis. In the optimal scenario, the data can be obtained directly from the real system, provided that there are enough sensors distributed throughout it. Nevertheless, this is unlikely, so dynamic software models are therefore required in order to calculate the variables in the different flows of the system over time. TRNSYS is one of the most popular software for building systems simulation and is widely used in research. For example, J.F. Belmonte et al. [13] employed simulations with the TRNSYS tool to ascertain the energy savings associated with the operation of solar systems. Conversely, Niaki eta al [14]. used TRNSYS to model and simulate the annual performance of a hybrid solar thermal and geothermal heat pump system in a residential building, thereby enabling them to analyse the impact of different types of heat exchangers and perform economic evaluations for different climate scenarios in Iran.

Therefore, the main objective of this article is to present and examine in detail the "Towards Dynamic Thermoeconomics" (TdT) application, a tool for analysing the dynamic thermal systems of buildings, including a special innovation to deal with inertial components, for subsequent thermoeconomic analysis.

For this purpose, two case studies involving two thermal systems are simulated in TRNSYS and thoroughly analysed with TdT. One case study covers DHW, while the other covers the heating demand, see Fig. 1. On the one hand, the demand for DHW represents, on average, 14.8 % of the energy consumption in the residential sector in the European Union [11]. On the other hand, heating accounts for 64.4 % of the final energy consumption of the EU in the residential sector in 2021, [12]. In addition, both systems are analysed at 8 sites in Spain, each corresponding to a specific climatic zone, with the objective of highlighting the impact of the T_0 outdoor temperature on advanced thermoeconomic analyses.

In essence, the main objective of this article is to demonstrate the accessibility and versatility of TdT as a tool for generating valuable results in the field of Thermoeconomics, by examining two common cases of thermal systems in buildings.

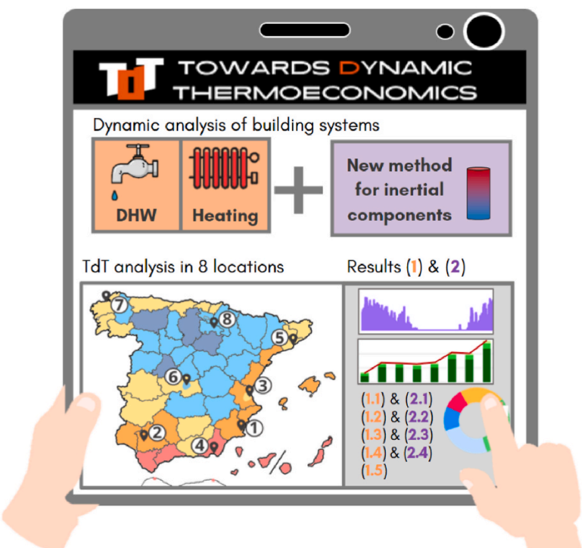


Fig. 1. Summary of the objectives: TdT analysis in two case studies in 8 locations with new method for inertial components.

2. Methodology

This section explains the TdT application, and gives an overview of the theoretical basis related to buildings in Spain.

2.1. Towards Dynamic Thermoeconomics (TdT)

"Towards Dynamic Thermoeconomics" is an innovative application that provides data for dynamic thermoeconomic analysis, among other things. This dynamic approach is essential, as it enables real-time thermoeconomic diagnoses of thermal systems in buildings, which facilitates the anticipation and detection of failures in the facilities.

TdT offers a number of notable benefits, including flexibility in calculating energy and exergy flows, energy and exergy balances, irreversibilities and energy and exergy efficiencies in different types of building systems. Additionally, it is an open-source application developed in Python [15], which makes it accessible to the community and allows exporting the results in many file formats, thus simplifying its use and sharing. It is also capable of working with large volumes of data, which results in significant time saving and it is simple to use. In summary, this application is not only powerful in its analysis, but also user-friendly, making it useful for a variety of professionals interested in Thermoeconomics.

2.1.1. Mathematical basis of TdT

To develop TdT, the *exergy methodology* [16] has been used, which simultaneously considers the 1st and 2nd laws of Thermodynamics. In addition to the classical thermodynamic analysis of mass and energy balances, the exergy balance enables quantifying irreversibilities and identifying the components that are most affected.

In addition to exergy analysis, the thermoeconomic analysis includes economic concepts and value judgements. For this, apart from the *physical structure* of the system (based on component incoming and outgoing mass and energy flows), it is necessary to define its *productive structure*, which is a set of relationships that define the interactions between components and the environment based on the Product (P) and Fuel (F) concept. Unfortunately, the productive structure is not unique, but can have different configurations, even with a single physical structure [17], which depends on the researcher's expertise and objectives. Consequently, the P represents the purpose of each subsystem, while F indicates the quantity of resources required to generate products, by-products or wastes. In this case, the P and F are defined by their exergy, following the *Exergy Cost Theory* of M.A. Lozano and A. Valero [18].

As is well known, unlike energy, exergy is not conserved. Therefore, if the system boundaries are expanded so that heat losses reach the T_0 outdoor temperature, the irreversibilities, I, represent the losses in a thermodynamic process, i.e., the amount of Fuel that is not transformed into Product because of the quality degradation during the processes:

$$I = F - P \tag{1}$$

Accordingly, TdT employs the exergy method and incorporates the principles of thermoeconomic analysis, thereby defining the dynamic productive structure for further thermoeconomic analysis.

For its part, the exergy of each flow depends on its nature.

- External resource flows (B_{ER_i}) feeding the generation component, which can be fossil, electricity, biomass, etc:

$$B_{ER_i} = E_{ERi} \bullet QF_{ER} \bullet \Delta t \tag{2}$$

- Material flows (B_{mf_i}), generally referring to water flows inside the heating, cooling or DHW distribution circuits:

$$B_{mf_i} = m_i \bullet c_{p_i} \bullet \Delta t \bullet \left((T_i - T_0\ ) - T_0 \bullet ln\left(\frac{T_i}{T_0}\right)\right) \tag{3}$$

- Tank charge flows (B_{TC_I}), which represents the accumulated exergy in a given period of time, when its internal energy increases:

$$B_{TC_I} = V_T \bullet C_{p_i} \bullet \rho_i \bullet \left((T_{i_t} - T_{i_{t-1}}\ ) - T_0 \bullet ln\left(\frac{T_{i_t}}{T_{i_{t-1}}}\right)\right) \tag{4}$$

- Tank discharge flows (B_{TD_i}), which represents the exergy decrease, in a given period of time, when its internal energy decreases:

$$B_{TD_i} = V_T \bullet C_{p_i} \bullet \rho_i \bullet \left((T_{i_{t-1}} - T_{i_t}\ ) - T_0 \bullet ln\left(\frac{T_{i_{t-1}}}{T_{i_t}}\right)\right) \tag{5}$$

- Heat flows (B_{H_i}), such as heating and cooling demands:

$$B_{H_i} = E_{Hi} \bullet F_{car} = E_{Hi} \bullet \left(1 - \frac{T_0}{T_{indoor}}\right) \tag{6}$$

where, E_{ERi} is the energy of the external resource flow i; QF_{ER} is the quality factor of the external resource; Δt is the time interval; m_i is the mass flow of time i; C_{p_i} is the specific heat of flow i; T_i is the temperature of flow i; T_0 is the outdoor temperature; V_T is the volume of the tank; ρ_i is the density of flow i; T_{i_t} is the temperature of the flow i, at time t; $T_{i_{t-1}}$ is the temperature of the flow i, at the time t-1; E_{Hi} is the energy of the heat flow I; F_{car} is the Carnot factor; T_{indoor} is the indoor comfort temperature defined according to RITE [19].

2.1.2. Parts of TdT

The application consists of 17 Python files, each of which corresponds to a specific function. The first file calls the remaining functions, the second file collects the information provided by the user, the next 7 files calculate energy and exergy flows, energy and exergy balances, energy and exergy efficiencies and irreversibilities; and the last 8 files, which are optional and related to the novelty, are analogous to the previous 7 files, but deals with the inertial tanks, if there are any. After all, when an inertial tank exists in the facility, some ambiguous cost-cases must be avoided, as detected by Prol-Godoy et al. [20].

Inertial components permit separating the moments of heat generation and consumption, thereby decoupling the instantaneous dependence of the primary and secondary circuits through charging and discharging them. This allows the total power of the system to be reduced and demands to be met without the necessity for instantaneous generation. Therefore, there may be periods when the demand is met directly from the tank discharge, or periods when, in the absence of demand, the tank is charged from the primary. Paradoxically, if Dynamic Thermoeconomic theory is applied to calculate the instantaneous costs, the cost of demand when covered by direct discharge is zero (i.e., one can think that such energy is free). However, in order to discharge the tank, it is necessary to first charge it by consuming energy resources and paying for them. This leads us to conclude that, in order to optimise control, it is necessary to avoid loading moments and to give priority to discharge moments, a fact that is meaningless in itself. Therefore, the methodology elaborated in the TdT preserves the dynamic nature of the analysis, but avoids this type of inconsistency by incorporating the following innovation into the analysis, see Fig. 2.

- To begin with, the programme identifies the most repeated tank temperature, $T_{tank,rep}$, and defines discontinuous time periods, as illustrated in Fig. 2. These periods are defined by the temperature at the beginning and the end of the period corresponding to the selected $T_{tank,rep}$ temperature.
- Subsequently, the thermoeconomic analysis is conducted, considering only those dynamic accumulate periods where the energy consumed for loading is compensated with the energy discharged.

This approach enables identifying the optimal operating modes, defined as those with the lowest cost, during dynamic periods; additionally, allows comparing operating modes and avoids the generation of misleading results.

2.1.3. Data to be entered in TdT

Data is inserted in the application in two ways.

1. **Data in external files or collected on site:** This includes data on thermodynamic variables over time (mass flow rates, temperatures, pressures, etc., of each time-step), according to their number on the physical structure. These data may be entered via an external file prior to executing TdT, or alternatively, it may be read instantaneously from the facility.
2. **Data entered at the beginning of the execution:** In this second category, the application poses a series of questions to be answered on the spot:
   - Thermodynamic Data Time-Interval: the user must specify the time-step of the thermodynamic data monitoring system.
   - Physical Structure: at this point, the user must delineate the nature of each energy-flow including external resource flows (B_{ER_i}), material flows (B_{mf_i}), tank flows (B_{TC_i} and B_{TD_i}) and heat flows (B_{H_i})).
   - Productive structure: the user needs to specify the fuels and products that make up the productive structure.

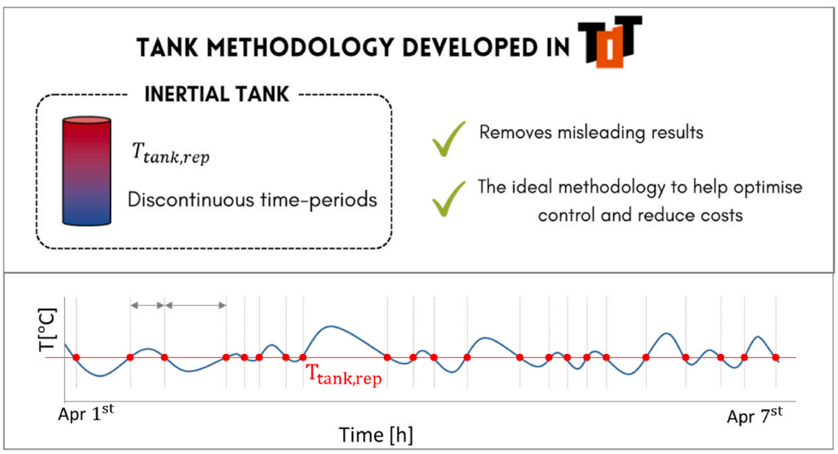


Fig. 2. Tank method fot TdT.

In addition, TdT provides the option for the user to define the $T_{tank,rep}$ or, alternatively, TdT will automatically calculate the most repeated tank temperature to perform the novel analysis based on such a temperature.

2.1.4. TdT results

The application exports a *results* file (1) consisting of 5 reports and, if there is a tank, it also generates the *results* $T_{tank,rep}$ file (2), which adds 4 further reports, see Fig. 3. The reports of file (2) are analogous to those of (1), but with the additional suffix *tank,* because the discontinuous time intervals in which the tank is at $T_{tank,rep}$ are considered.

As can be observed, TdT provides a comprehensive range of analytical tools to assess thermal systems in buildings. Additionally, the results are compatible with the software developed by Picallo et al. [8], which calculates thermoeconomic variables, such as the economic and environmental dynamic costs. Therefore, TdT is a versatile open-source software compatible with other dynamic thermoeconomic tools.

2.1.5. Input and output summary

In summary, as shown in Fig. 4, TdT requires a number of inputs that result in valuable outputs to analyse the dynamic behaviour of thermal building systems.

2.2. Climatic zones in Spain

The Technical Building Code (CTE) of Spain, as outlined in its Basic Document on Energy Saving DB-HE [22], divides the country into different climatic zones, which are essential for implementing energy efficiency regulations and standards in buildings. The climatic zones are designated by a letter representing the climatic severity in winter and a number corresponding to the climatic severity in summer, according to two main factors: the altitude of the building plot and the province where it is located.

3. Case study

In this work, two simple and common thermal systems have been selected to facilitate the comprehension of the results: the first (a) covers the DHW demand and the second (b) the heating demand, both modelled in TRNSYS software [21]. The user defines each productive structure and the additional data requested by TdT and, afterwards, the corresponding thermodynamic data are extracted from each system, in each time-step, according to their physical structure, see Fig. 5.

Accordingly, this paper applies the TdT tool to both systems in eight different climatic zones, ranging from highest to lowest $T_{0,avg}$ yearly average outdoor temperature. Fig. 6 presents the information of the province and climatic zone for the selected sites as well as the T_0 during the year and the $T_{0,avg}$. Therefore, TdT is applied 8 times, one for each system, since, as highlighted in A. Hernández-Arizaga [23], the exergy of the material flows, such as water in HVAC systems, is linked to the value of the reference temperature,

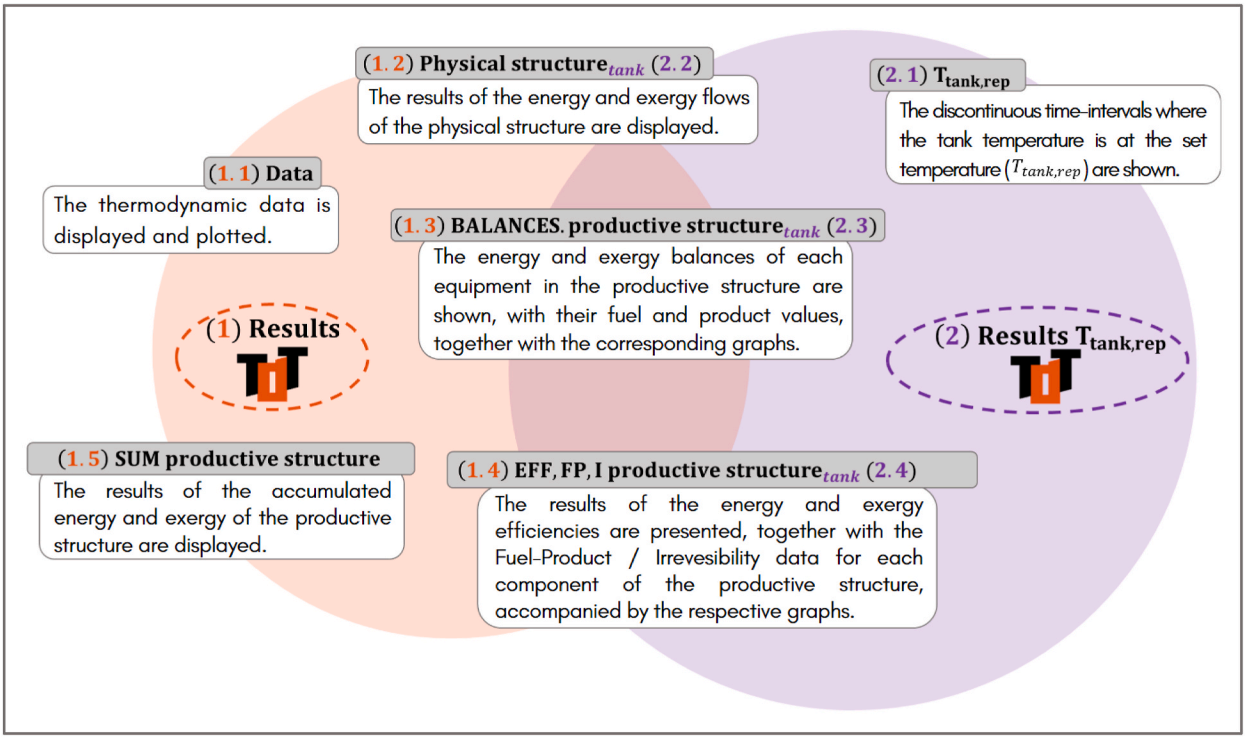


Fig. 3. TdT results.

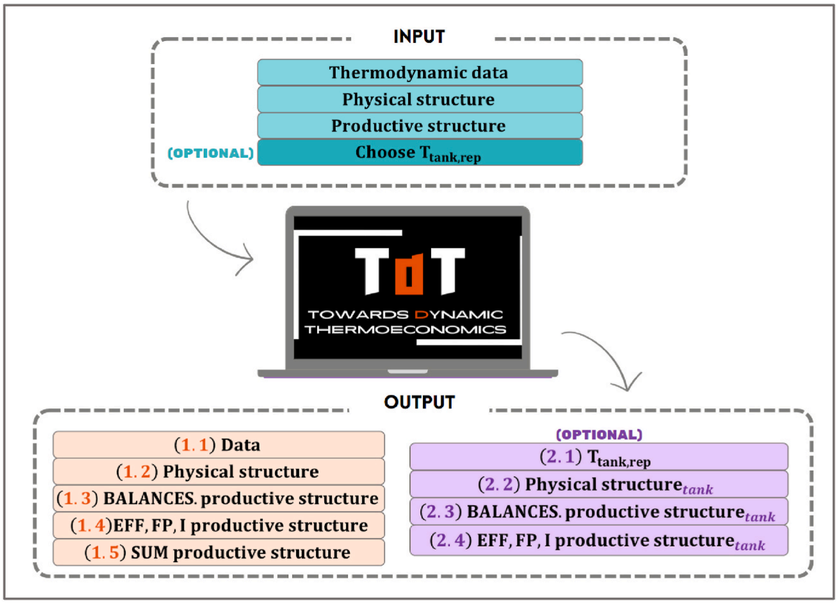


Fig. 4. Input and output summary.

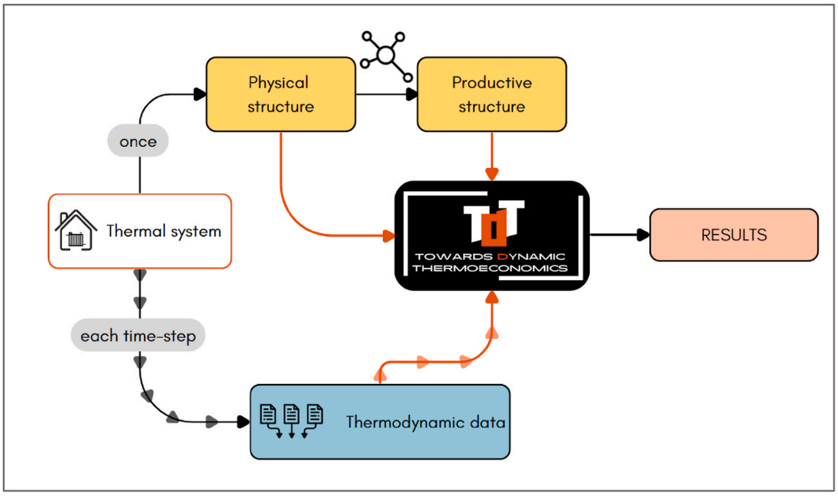


Fig. 5. Process to obtain TdT results.

which is the T_0 outdoor temperature in each case study. Therefore, and considering the low computational cost required by the TdT, the objective is to highlight the results provided by this innovative tool and its added value, which helps, for example, comparing facilities in different locations.

3.1. Definition of the systems

As previously stated, the selected facilities supply (a) DHW and (b) heating demands to a single-family house with two inhabitants. The demand flow rate profile for DHW [l/h] is determined according to the DB-HE of the CTE [22], which depends on the number of residents and use. Furthermore, the energy demand of DHW [kWh], supplied at 45 °C, depends on the T_{net} temperature of the net, which is related to the T_0 outdoor temperature. The heating demand profile [kWh] is calculated using the approximate degree-day method with a base temperature of 15 °C, as set out in Refs. [24,25]. Consequently, both demand profiles, DHW and heating, depend on the instantaneous T_0 outdoor temperature of each site.

The two systems consist of a 28 kW natural gas condensing boiler and two hydraulic pumps of 0.27 kg/s and 0.694 kg/s, respectively. In addition, the (a) DHW system contains a heat exchanger and a 1 m^3 storage tank. In contrast, the (b) heating system comprises a 1 m^3 hydraulic compensator and a radiator that dissipates the required heat to satisfy thermal comfort conditions, see Fig. 7, which also includes the number of flows used to define the physical structure.

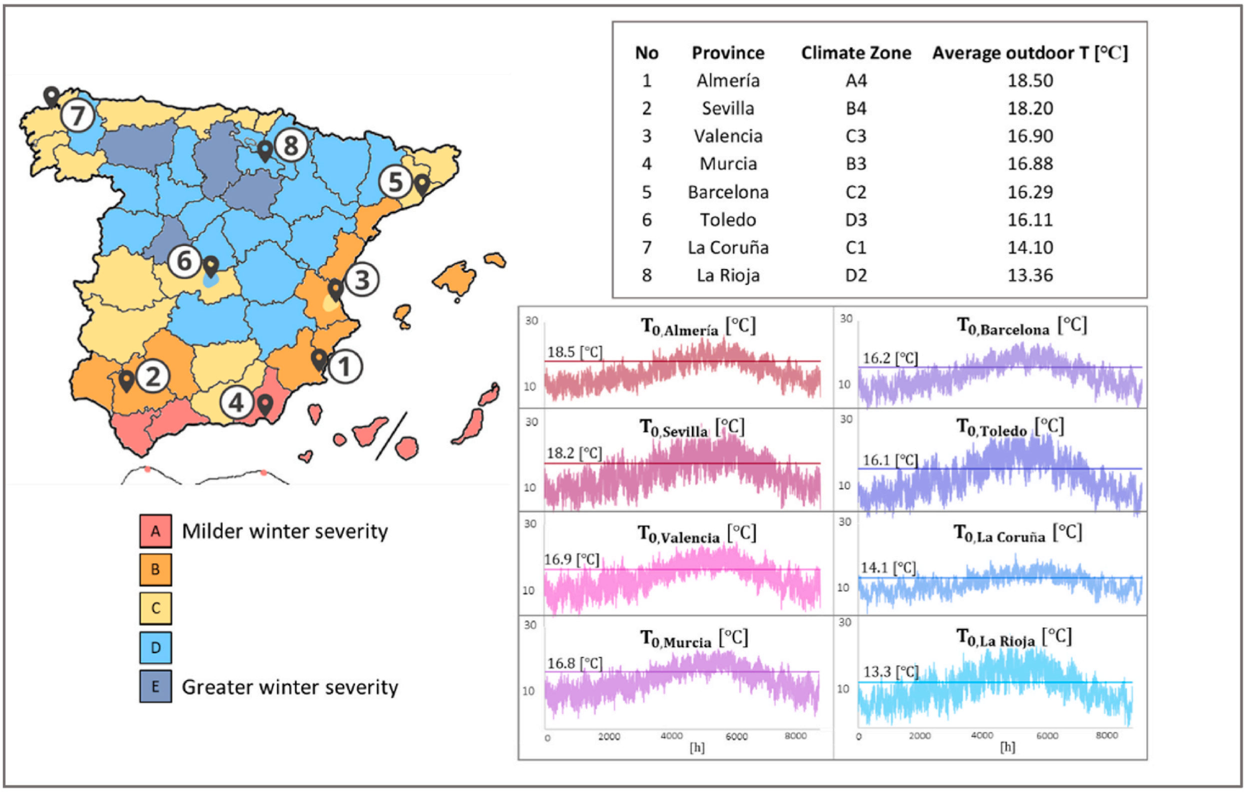


Fig. 6. Location and climatic zones of 8 facilities in Spain according to their winter climate severity.

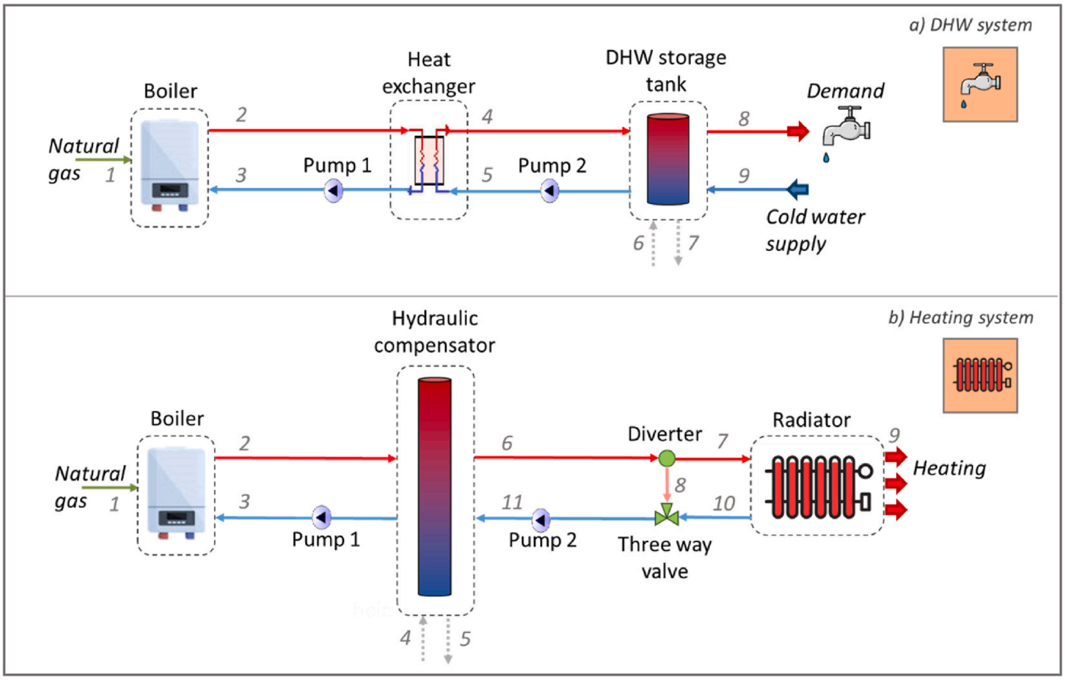


Fig. 7. Diagram of the 2 systems.

According to the control of the (a) DHW case, the boiler is activated when the storage tank temperature is below 60.5 °C and deactivated when it exceeds 62 °C. Conversely, the DHW is stored when the temperature at the primary inlet of the heat exchanger is 5 °C higher than the tank temperature and stops when it is below 2 °C.

In the context of the (b) heating system control, pump 2 is activated when there is heating demand. In addition, if the hydraulic compensator falls below 50 °C, both the boiler and pump 1 are activated. This process continues until the hydraulic compensator reaches 70 °C. In the absence of heating demand, all the components remain deactivated.

Both systems are simulated in TRNSYS over a one-year period with a 5 min time-step at the 8 corresponding locations. In this manner, the data of mass flows, temperatures and the required boiler energy input are obtained for each time-step, which constitutes one of the external files for TdT.

3.2. Data to enter in TdT

As previously stated, the user must first define the physical and productive structures of each facility by naming the flow nature and the F and P of each component. Secondly, the dynamic thermodynamic data file in each time-step must be entered. Fig. 8 shows the productive structure of both facilities (for more information on the construction of the productive structure, refer to Ref. [18]).

In addition, the TdT poses a series of inquiries, which are summarized in Table 1 (for the (a) DHW system) and Table 2 (for the (b) heating system).

4. Results

This section contains the results of the TdT of both systems at the 8 different locations.

4.1. General results

Due to the limited space available, this section presents only a selection of the results files obtained from the TdT of the first case study in Almería (A4: milder winter), related to the (a) DHW system, during the first week of April.

- Fig. 9 depict a portion of 1. *Result* file (1.1), which pertains to data provided by the user. This includes the required boiler energy input, temperatures of the various flows, as well as the outdoor temperature and mass flows of different circuits in each registered time-step, which is the time-step obtained from the thermal system data.
- As already stated, TdT incorporates a novel file associated with "2". The *results* $T_{tank,rep}$ considering the discontinuous time-intervals in which the tank is at $T_{tank,rep}$ in order to facilitate an unambiguous analysis. As an example, Fig. 10 shows the energy balances of the main components (result file: (2.3)) during the first week of April, wherein the irregular time intervals are displayed.
- Fig. 11 shows the exergy efficiencies of each component of the file (2.4) of *the results* $T_{tank,rep}$.

4.2. DHW system

This section, related to the DHW facility, compares the TdT results of the various climatic zones. Nevertheless, although the results are dynamic, for the sake of clarity, only the average values during the year are presented.

- To begin with, Fig. 12 shows the average exergy efficiency of the boiler, φ_{Boi}, in relation to the average outdoor temperature, $T_{0,avg}$, for each location. Conversely, the average energy efficiency remains almost constant, with $\eta_{Boi} = 90.0\%$. This is because, although the T_0 influences the T_{net} net temperature and hence the DHW demand, its influence is not relevant in the energy efficiency of the boiler.

Therefore, an increase in the T_0 outdoor temperature, reduces the φ_{Boi} boiler exergy efficiency. This highlights a worse use of energy

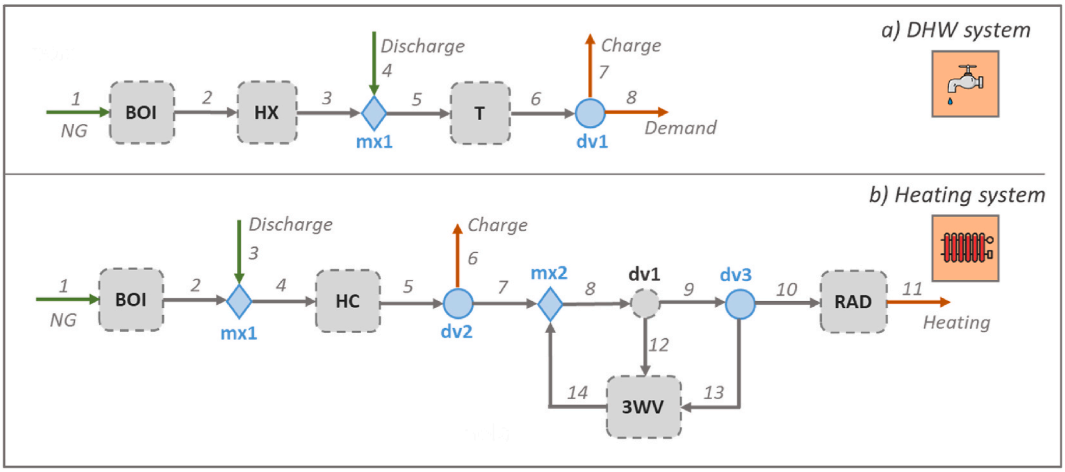


Fig. 8. Productive structure of the two systems.

Table 1
TdT questions and answers for DHW system.

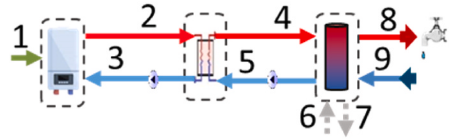
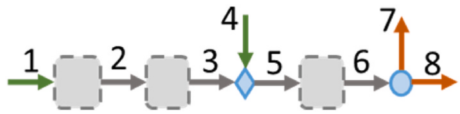
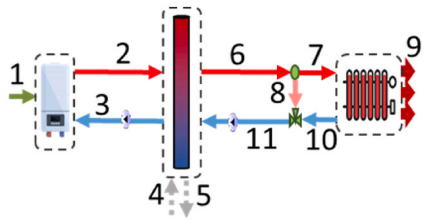
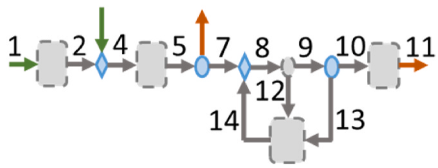
Time-step of registered data [h]		5/60
IS THERE ANY INERTIAL COMPONENT?		YES
PHYSICAL STRUCTURE		
N° of external resource flows	1	
Type of external resource	Natural gas	
N° of material flows	2,3,4,5,8,9	
N° of tank charge	7	
N° of tank discharge	6	
N° of incoming hot-flow in the tank	4	
N° of outgoing hot-flow from the tank	8	
Tank volume [m^3]	1	
PRODUCTIVE STRUCTURE		
N° of flags	8	
N° of components	5	

Table 2
TdT questions and answers for heating system.

Time-step of data [h]		5/60
IS THERE ANY INERTIAL COMPONENT?		YES
PHYSICAL STRUCTURE		
N° of external resource flows	1	
Type of external resource	Gas natural	
N° of material flows	2,3,6,7,8,10,11	
N° of tank charge	5	
N° of tank discharge	4	
N° of incoming hot-flow in the tank	2	
N° of outgoing hot-flow of tank	6	
Tank volume [m^3]	1	
Heating/cooling flows	9 (heating)	
PRODUCTIVE STRUCTURE		
N° of flags	14	
N° of components	9	

Once all the data has been entered, the TdT runs and creates the results files.

resources. Consequently, in the event of a climate change scenario, in which the outdoor temperature rises, the boiler must adapt to the new conditions in order to achieve favourable performance.

Fig. 13 shows, on the one hand, the accumulated irreversibilities of the main components in each location, as well as the total accumulated exergy consumption and the DHW exergy demands.

- It can be observed that the boiler always has the highest irreversibilities, accounting for approximately 90 % of the total, while the tank has the lowest.
- The location with the worst winter (8. La Rioja) exhibits the highest irreversibilities, due to the boiler's high irreversibilities, despite its high exergy efficiency, as illustrated in Fig. 12. This is due to the fact that it consumes the majority of the resources (F = 1.74E+10 J).
- Systems with cooler winters and lower average outdoor temperature $T_{0,avg}$ (7 and 8) consume a greater quantity of F_{TOT} total resources to produce the same DHW flow rate requirement [l/h]. This is because the T_0 outdoor temperature affects the cold water supply temperature, requiring a higher consumption of natural gas in the boiler in order to achieve the set DHW tank temperature above 60.5 °C.

4.3. *Heating system*

A comparison of the average energy and exergy performances of the heating system is not meaningful, given that the demand

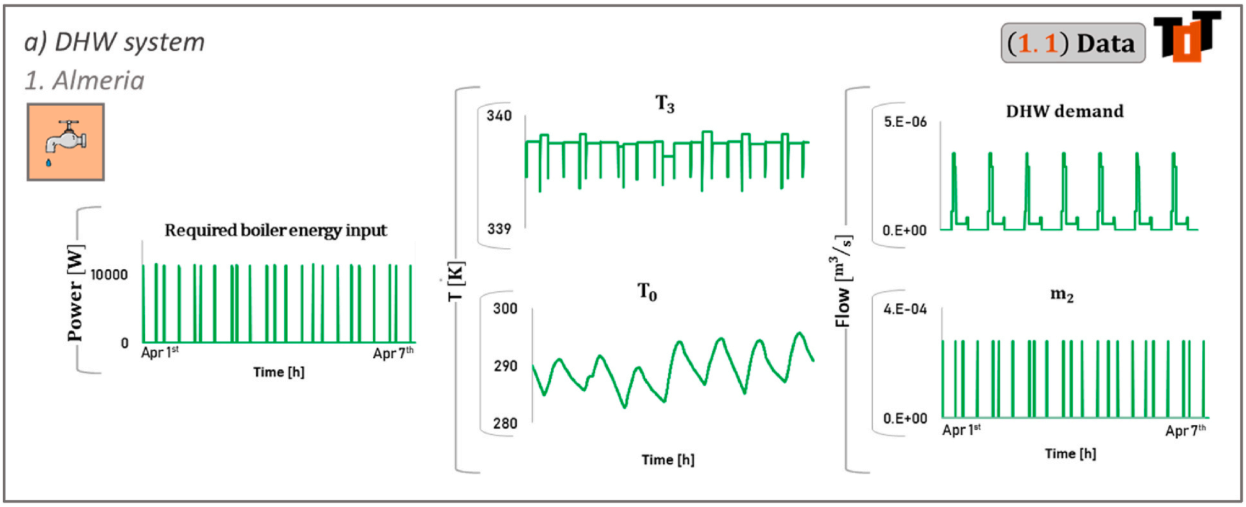


Fig. 9. Display of input data series in the TdT results.

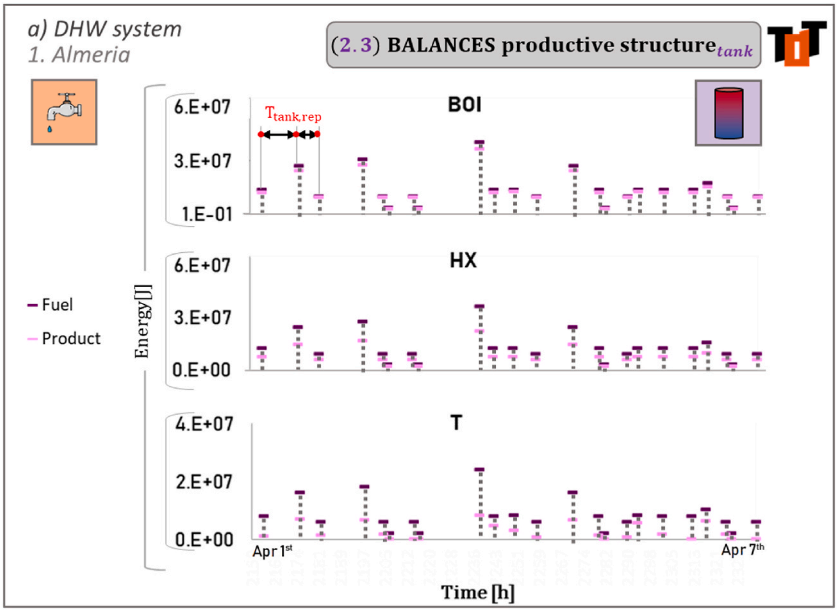


Fig. 10. Visualisation of energy balances with the tank methodology in the file 2. Results $T_{rank,rep}$.

depends on the location and the instantaneous T_0, the outdoor temperature, as shown in Fig. 14.

- Thus, in order to compare the boiler performance in each location, Fig. 15 plots the η_{Boi} energy and φ_{Boi} exergy efficiencies of the boiler, according to the T_0 outdoor temperature at which the boiler operates in each of the systems. As in the previous DHW case, the exergy efficiency decreases; while the T_0 outdoor temperature increases, even if the η_{Boi} energy efficiency remains constant. Thus, a higher T_0 outdoor temperature does not enhance exergy production in the boilers, despite consuming the same amount of resources, resulting in a product with a lower useful-work capacity.

Fig. 16 illustrates the irreversibilities of the principal components of each location in addition to the F_{TOT} and P_{TOT} of each heating system.

- Once more, the component with the highest irreversibilities is the boiler, accounting for approximately 90 % of the total irreversibilities.
- The coldest place (8. La Rioja), has the highest total irreversibilities, since the boiler has the highest irreversibilities due to its highest heating demand.

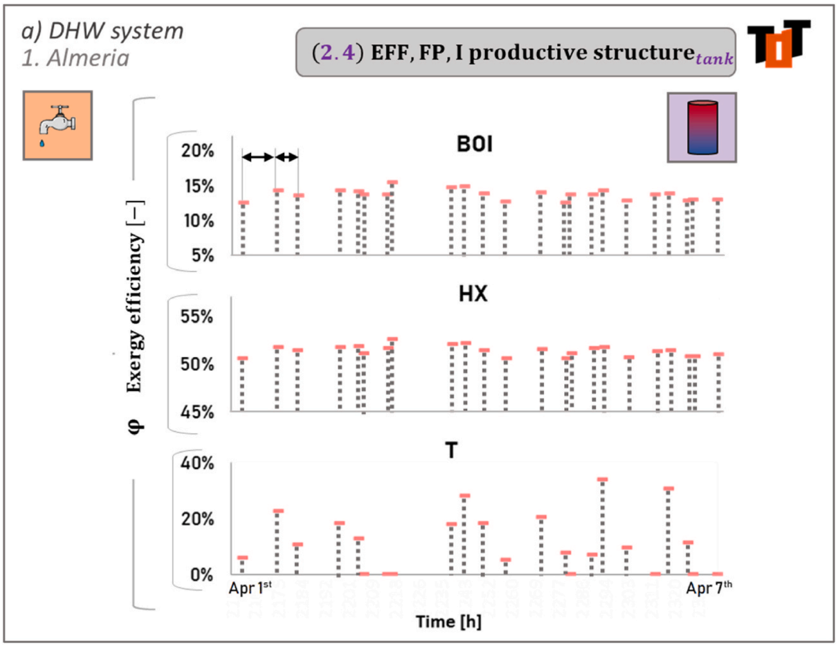


Fig. 11. Visualisation of exergy efficiencies with tank methodology in the file 2. Results $T_{rank,rep}$.

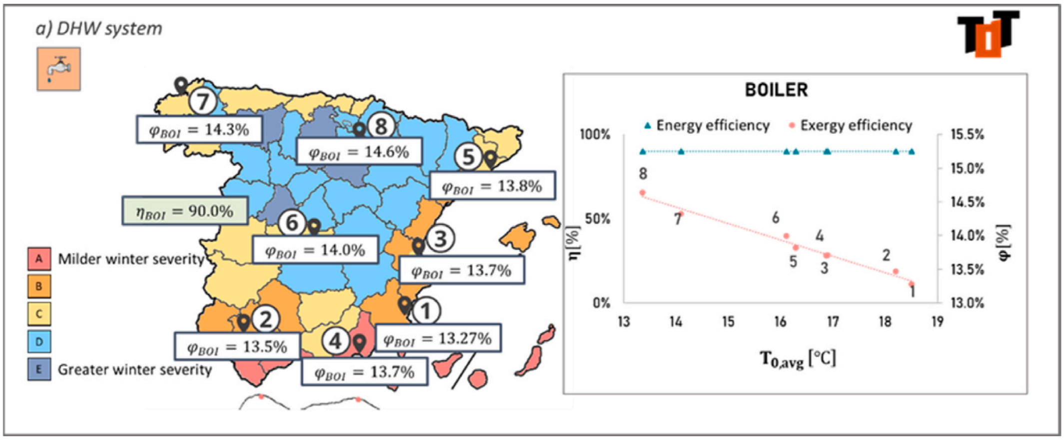


Fig. 12. Energy and exergy efficiencies of the boiler in each site related to the average outdoor temperature.

- In addition, the φ_{Heat} total average exergy efficiency of these systems ranges from 0.4 % to 1.3 %, while the η_{Heat} total average energy efficiency ranges from 13.2 % to 24.4 %. This is due to the bad exergy performance of the hydraulic compensator, with an average φ_{HC} exergy efficiency of between 42 % and 50 %. In other words, almost half of the exergy entering the hydraulic compensator is destroyed, with less than half being used to meet the heating demand; which is also destroyed in the radiator component itself.
- As previously stated, the exergy of the heating flow is calculated by multiplying its energy value by the Carnot factor $\left(1 - \frac{T_0}{T_{indoor}}\right)$, see eq. (6), which ranges between 0 and 1. Therefore, the final exergy product of the heating installation is considerably lower than the energy product.

5. Conclusions

This work develops and applies the Towards Dynamic Thermoeconomics (TdT) open-source application as a versatile tool to analyse dynamic systems, whose results are highly valuable for identifying thermal system weaknesses and conducting subsequent thermoeconomic analyses, aided by its compatibility with other Thermoeconomic software. Besides, dynamic results from TdT enable real-time comparison and fault detection, a capability not achievable with static results.

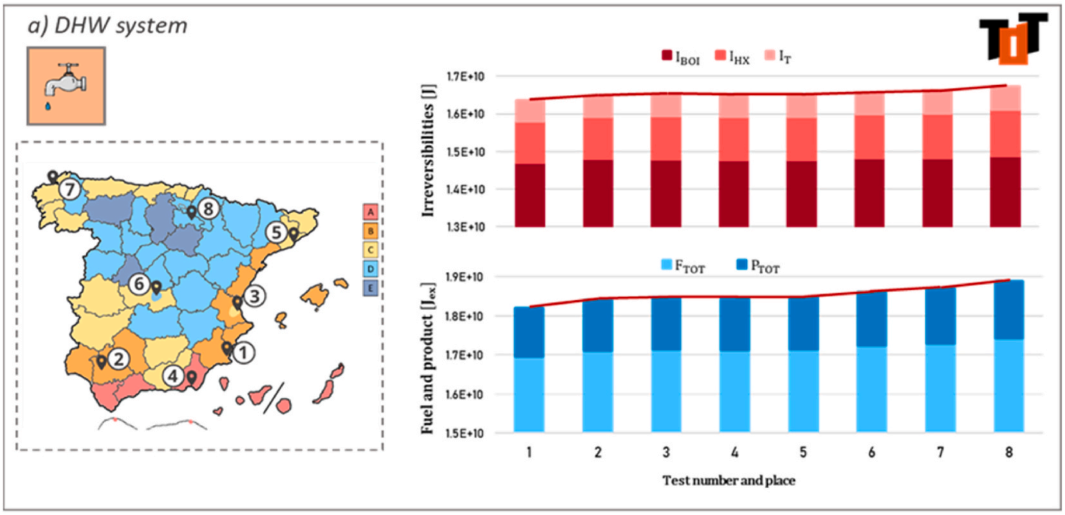


Fig. 13. Irreversibilities of main components and F and P of the DHW system in each site.

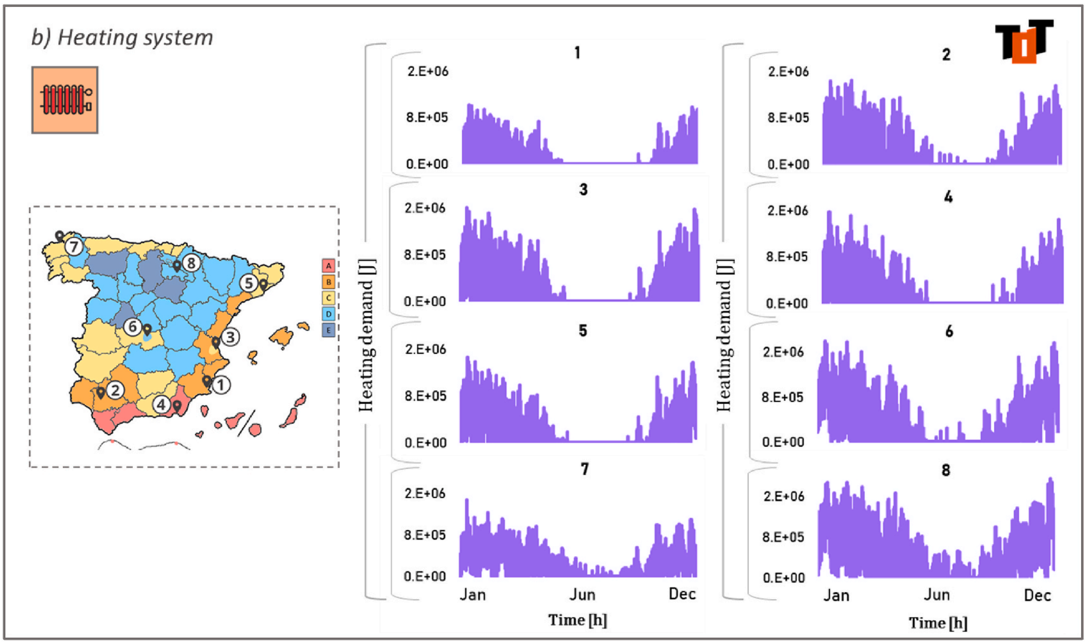


Fig. 14. Heating demands at all sites analysed.

Additionally, the novel inertial tank methodology in TdT enhances result accuracy, reducing the risk of misleading outcomes and facilitating informed decision-making regarding thermal system controls. This methodology detects the most repeated temperature $T_{tank,rep}$ to define irregular time-periods, thus maintaining the dynamism of the system but avoiding errors due to the decoupling between generation and demand moments, by attributing to each interval an equivalent amount of energy charging and discharging. This facilitates identifying system failures, thereby making TdT an even more valuable tool for management and diagnosis of thermal systems in buildings.

After explaining the parts and the internal framework of the TdT this paper tests the tool's by analysing a simple DHW and a heating system in 8 climatic zones of Spain, with the following main results.

- It appears that as the T_0 outdoor temperature increases by 38 % (from $T^8_{0,avg} = 13.36\ ^\circ C$ to $T^1_{0,avg} = 18.50\ ^\circ C$), the φ_{Boi} exergy efficiency of the boiler in both systems decreases, despite the η_{Boi} energy efficiency remaining constant. In the DHW system, the average yearly exergy efficiency of the boiler in both systems decreases by 1.4 % (from $\varphi^8_{Boi,DHW} = 14.63\%$ to $\varphi^1_{Boi,DHW} = 13.27\%$), despite the energy efficiency remaining almost constant ($\eta^8_{Boi,DHW} \approx \eta^1_{Boi,DHW} \approx 90\%$). For this reason:

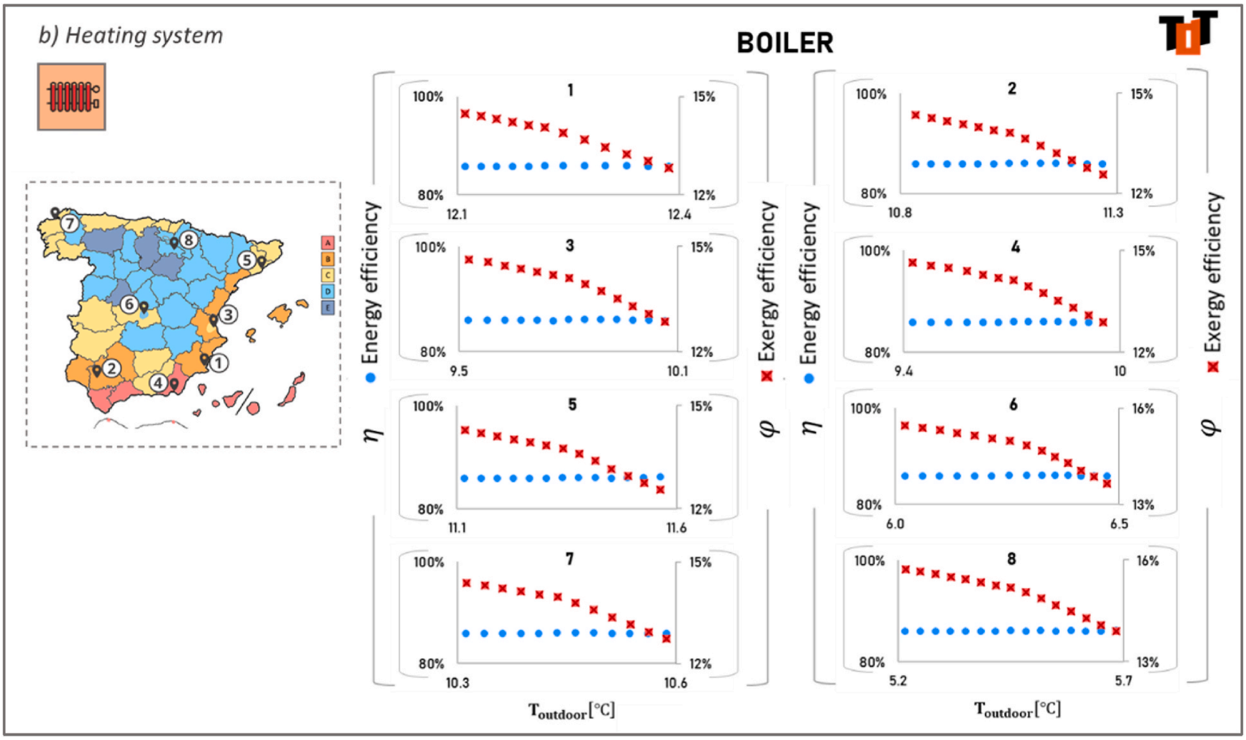


Fig. 15. Relationship between the energy and exergy efficiencies of the boiler and the outdoor temperature at the analysed sites.

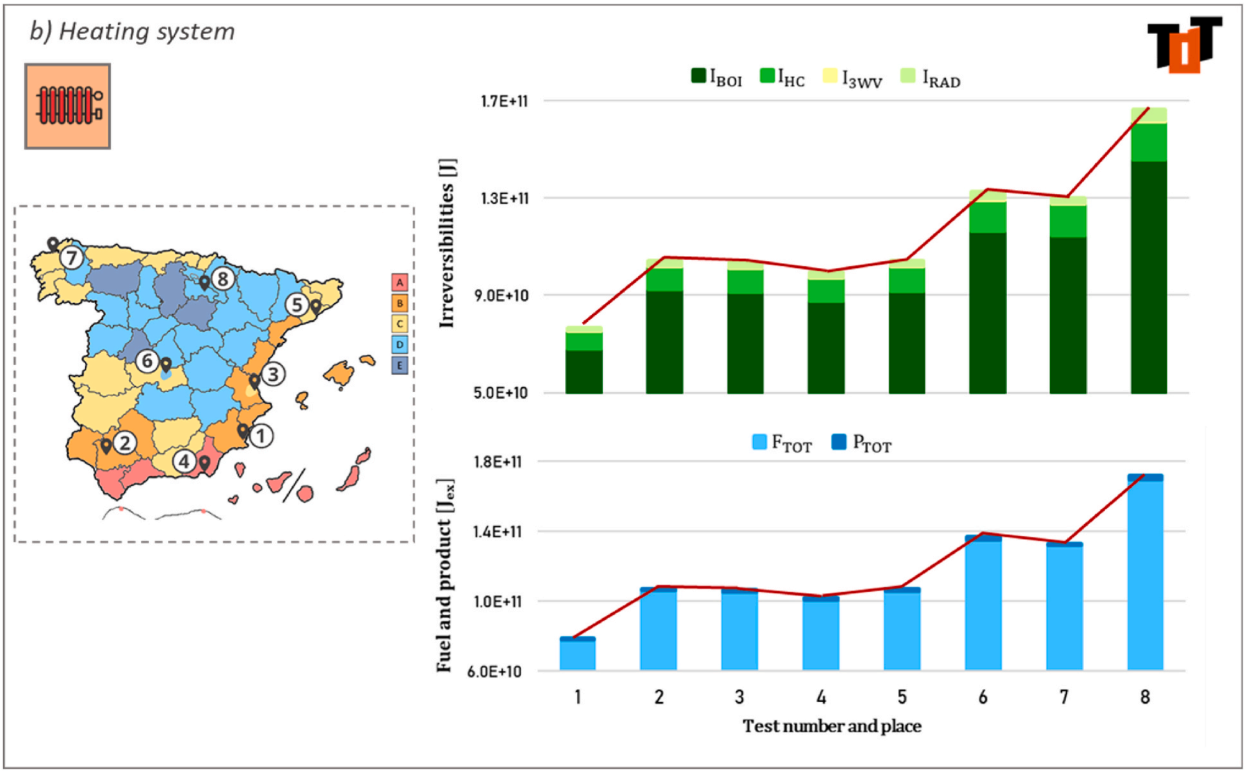


Fig. 16. Irreversibilities of main components and total F and P of the heating system in each site.

  - It is concluded that a scenario with higher T_0 outdoor temperatures is unfavourable for boiler operation, as the exergy demand of the products, DHW and heating, decreases when the supply temperatures approach the reference one.
  - Incorporating the exergy variable into building analysis is crucial, as it provides insights into the quality degradation of energy transformations, an aspect not captured by energy analyses alone.
- In both systems analysed, the component with the greatest irreversibilities is the boiler ($I_{Boi,DHW} \approx 1.5 \cdot 10^{10}\ J$ and $I_{Boi,Heat} \in (7, 15)\cdot 10^{10}\ J$), followed by the heat exchanger in the DHW system ($I_{HX,DHW} \approx 1.1 \cdot 10^{10}\ J$) and the hydraulic compensator ($I_{HC,Heat} \in (0.7, 1.6) \cdot 10^{10}\ J$) in the heating system.

These conclusions highlight the importance of the versatile TdT tool, which provides a comprehensive range of results compatible with other dynamic thermoeconomic tools. It includes dynamic analysis with the novel methodology for inertial components, which are present in almost all centralised building systems. In essence, TdT gives valuable insights for decision-making aimed at improving the efficiency and sustainability of thermal systems in buildings.

CRediT authorship contribution statement

Irati Prol-Godoy: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **F. Javier Rey-Martinez:** Writing – review & editing, Validation. **Ana Picallo-Perez:** Writing – review & editing, Validation, Resources, Methodology, Conceptualization, Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Irati Prol Godoy reports equipment, drugs, or supplies was provided by Euskampus Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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