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Simulation-Based Education Tool for Understanding Thermostatically Controlled Loads

Gabriel Gomez-Ruiz [1,*], Reyes Sanchez-Herrera [1], Jose M. Andujar [1] and Juan Luis Rubio Sanchez [2]

[1] Research Centre CITES, University of Huelva, 21007 Huelva, Spain; reyes.sanchez@die.uhu.es (R.S.-H.); andujar@uhu.es (J.M.A.)
[2] School of Sciences and Engineering, Distance University of Madrid (UDIMA), 28400 Collado Villalba, Spain; juanluis.rubio@udima.es
* Correspondence: gabriel.gomez@diesia.uhu.es

Abstract: Thermostatically controlled loads have great potential to make a significant contribution to improving energy efficiency in the building sector, which is responsible for 40% of greenhouse gas emissions in the EU. This, in addition to the environmental damage, represents a huge expense in terms of the electricity bill. Therefore, it is very important to train engineers on how to design energy management systems for TCLs. With this goal in mind, it would be very useful to have a simulation-based educational tool (SBET) to understand thermostatically controlled loads, their characteristics, and the possibilities in terms of energy efficiency. In addition, it would be very useful if this tool could be introduced in engineering curricula to help students become better trained and enter the labor market with more opportunities. Based on the shortcomings detected, this work develops an SBET specifically designed to teach on the subject of TCLs (SBET-TCLs), both about their intrinsic characteristics and their better management. To verify the developed SBET-TCLs, it was tested in a real scenario: a survey was carried out among the students of the subject 'Alternative Energy Sources' in the degrees of Industrial Engineering. The results show that the use of an SBET-TCLs has very positive effects on the learning process.

Keywords: simulation-based education tool; thermostatically controlled loads (TCLs); energy efficiency; undergraduate engineering students

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1. Introduction

The current geopolitical situation and the enormous problem of climate change to which the world is now subjected, require solutions in the short term to alleviate energy costs on the one hand and, on the other, to begin the gradual process of decarbonization of the planet that will allow at least a glimpse into the future of guaranteed sustainability. Focusing on the electricity sector, it is necessary to decisively address two major problems: the reduction of electricity costs (at the end of the chain, i.e., the bill paid by the user) and an increase in the use of renewable energies. In this complex scenario, thermostatically controlled loads (TCLs), mainly electric space heating/cooling, refrigerators, freezers, and electric water heaters, have great potential to minimize electricity bills and maximize the use of renewables in electricity systems [1]. In fact, heating and cooling loads represent around half of the total energy consumption of EU countries [2]. However, due to the thermal characteristics of the TCLs, by applying appropriate control strategies it is possible to increase or reduce their power, or even temporarily stop a TCL's connection without loss of thermal comfort for the user, simply by taking into account the intrinsic thermal storage capacity of a building [3]. Thus, to reduce global energy consumption and CO_2 emissions in buildings, TCL modeling and control is an excellent resource [4] since they provide numerous benefits when energy demand is high [5] or energy cost needs to be minimized [6].

Based on the above, despite being a novel field of research, it is necessary to incorporate the management of TCLs in the curricula of students, with an emphasis on higher education and engineering careers.

The constant evolution of society and technology implies the need for constant revision of engineering curricula [7]. In engineering education, theoretical concepts are often complex and difficult to bring to real life, thus, practical activities play a very important role in learning. However, open-air activities [8] or real laboratory experiments [9] require expensive equipment, are time-consuming, and can involve a certain amount of danger. In particular, teaching TCL control in real laboratories requires complex and expensive equipment, as well as environmental conditions (those corresponding to a real inhabited building: home appliances, insulation, room temperature, etc.), and availability of time of use, which are all very difficult to achieve.

To overcome the above-mentioned drawbacks, simulation-based educational tools (SBETs) can be an excellent choice to complement and enhance the quality of learning about TCLs.

In general, SBETs have been playing an important role in the teaching–learning process for years [10]. Indeed, SBETs were shown to help both teachers, by optimizing educational content, and students, by improving comprehension and increasing interest and creativity [11].

There are studies that analyze the learning progress of groups of students who use SBETs versus those who do not [12]. The results show that groups of students using SBETs have a better learning rate [13]. In fact, according to [14], SBETs allow students to retain up to 90% of the educational content, as opposed to reading (10%) or listening (20%).

To place the student at the center of the learning process, novel approaches to learning in science education have emerged in recent years. Examples include collaborative [15], problem-based [16], project-based [17], and competency-based learning [18], along with the flipped classroom [19] and gamification techniques [20], among others. Practices carried out in classroom through these methodologies can be enhanced with different technological applications, resulting in a pedagogical approach known as blended learning [21]. Thus, SBETs are a suitable resource to overcome the challenges and difficulties of the learning process [19,22].

The current digital transformation process has also promoted these new educational approaches. However, until the COVID-19 pandemic, its impact had not been as pronounced as it is now [23,24]. In fact, it is after the COVID-19 pandemic that a European Union (EU) policy initiative known as the Digital Education Action Plan (2021–2027) appeared, whose aim is to support the adaptation of member states' education and training systems in the digital age [25].

Perhaps at the forefront of this transition towards teaching with the student as the protagonist of his own learning process towards a more digital education are the universities [26]. In this framework, students' interest and motivation increase, and the development of their skills is facilitated.

SBETs can be self-developed [27–29] or commercial [30–33], and involve virtually all engineering degrees. In this way, there are applications for them in electrical [34], electronic [35,36], communications [37], control [38,39], computer science [40], thermal energy [41] or mechanical spheres [42], among others.

Focusing on the field of TCLs, there are some simulation-based tools in the literature that can manage them [43–47], not specifically, but as part of a network, usually an electrical network. Moreover, although these tools can be used in educational environments, they are not developed for that purpose; therefore, among other things, they lack the necessary utilities to deepen the intrinsic knowledge of TCLs. In this sense then, they cannot be considered SBETs. Thus, GridLAB-D™ 4.0 [43] was developed by the U.S. Department of Energy (DOE), which envisions the management of TCLs as just another load in an electrical distribution system. On the other hand, the Object-oriented, Controllable, High-resolution Residential Energy (OCHRE) tool [44] does not deal in a specific way with TCLs but can include them in its simulations as thermal loads. As for OpenDSS 9.7.1.1 [45], this is an electrical power distribution system simulator that can handle TCLs as loads with specific hourly operations but not as a control system to optimize them. Finally, [46,47] are designed for microgrid simulations. Thus, RAPSim 0.95 (Renewable Alternative Powersystems Simulation), [46], is a free and open source microgrid simulation framework whose main objective is to foster the understanding of power flows in smart microgrids with renewable sources. Again, TCLs are just another load. With regard to [47], HOMER Pro® 3.14 microgrid software by HOMER Energy is a high-level simulation payment framework. Its capabilities are enormous, but it does not delve or even go into the nature of TCLs in an academic setting.

After analyzing the state-of-the-art of the availability of SBETs in the literature for the in-depth study of TCLs, it was concluded that there were no tools suitable for academic environments. Consequently, this was the motivation for the work presented in this article: a specific SBET for TCLs (SBET-TCLs).

This paper presents an SBET-TCLs that allows for the in-depth study of the dynamic behavior, energy consumption, and best management of TCLs in building (in the following and throughout the paper, building, house or dwelling may be used interchangeably) applications: electric space heating/cooling, refrigerators, freezers, and electric water heaters. Due to the experience in previous developments, the simulation tool was implemented using Easy Java/JavaScript Simulations (EJS) [48], an open source tool written in Java, mainly dedicated to teaching and learning.

The main objective of this research is to improve, through the development and use of a new SBET, the learning in relation to TCLs, facilitating their understanding and practical applicability. Then, in line with the authors' previous educational work and with the aim of measuring the suitability of the proposed SBET, a survey was carried out among the students of the 'Alternative Energy Sources' subject within Electrical Engineering, Industrial Electronic Engineering, Mechanical Engineering, and Industrial Chemical Engineering degrees at the University of Huelva. The results show that the use of the developed SBET improves the learning process on TCLs in these degrees.

Based on everything discussed in this section, this paper is novel for the following reasons:

(1) Prior to the proposed SBET, there were no tools suitable for academic environments specifically focused on the TCL teaching/learning process.
(2) The proposed SBET delves deeper into the intrinsic behavior of TCLs, i.e., it allows them to be studied at a detailed level.
(3) The proposed SBET allows for modeling TCLs as state–space models, which captures their dynamics.
(4) The proposed SBET works with parameterized models that can be easily modified by the student according to the application under study.
(5) The proposed SBET is a very intuitive and easy framework, which is essential in an educational environment, otherwise the student will be demotivated by the workload.
(6) The proposed SBET was incorporated into curricula and tested in real engineering degree scenarios.
(7) To the authors' knowledge, there is no TCL model in the literature that is more intuitive, simple, and easier to calculate and interpret than the one presented in this article.
(8) The developed tool is the first step in the construction of an experimental platform to test different strategies to control TCLs and to confirm TCL behavior under different conditions. This platform could also be used to characterize any kind of TCL other than those considered in this tool.
(9) The developed tool is also a first step towards investigating aggregated TCLs as a means of controlling demand on a power system.

The remainder of this paper is organized as follows. Firstly, the article presents the theoretical framework and the methods to know some necessary parameters in the developed models in Sections 2.1 and 2.2, respectively. Then, the educational framework is described in Section 2.3. A description of the developed simulation-based educational tool is given in Section 3. Next, the results about the technical performance of the developed simulation-based educational tool and their evaluation as an educational resource are reported in Sections 4.1 and 4.2, respectively. The results obtained are discussed in Section 5. Finally, some conclusions are drawn in Section 6.

2. Materials and Methods

The materials and methods used in the SBET development can be divided into two distinct parts. The first one refers to the technical aspects of the tool, that is, what is its scientific basis thermodynamically speaking. The second refers to the educational aspects of the tool, that is, its evaluation as an educational resource.

2.1. Theoretical Framework of the Developed Simulation-Based Education Tool

As already explained, the usual TCLs in a building are considered in the study: electric space heating/cooling, refrigerators, freezers, and electric water heaters. Each TCL is modeled following an approach known as grey-box model [49], which are dynamic thermal models (state–space models) identified from experimental measurements [50]. The main concept of the grey-box model is to group and represent the different components of the TCLs by means of thermal resistances (R), representing the difficulty in the heat transfer (i.e., the degree of tightness of the thermal enclosures), and thermal capacities (C), which represents the capacity to store energy in the form of heat. This is analogous to the way an electrical circuit hinders the passage of electric current through resistors and stores electrical energy through capacitors. As a simple example, consider a building in which air infiltration losses through the windows are not taken into account, nor the temperature difference between the ambient temperature and that of the walls. In this case, any room with exterior walls has two thermal nodes (interior and exterior wall surface) with their respective thermal capacities connected by a thermal resistance representing the rate of convective and radiative heat exchange between them through the wall.

This type of RC model must be identified, i.e., applied to the example of the building, the different values of R and C in the different parts of the building due to the different TCLs have to be calculated or measured [51]. The value of C depends on the node's ability to store energy in the form of heat. For example, the outer surface of a wall that absorbs energy depending on the solar radiation, its color, and its physical composition. Regarding R, the higher the thermal insulation of the wall, the higher its value because it opposes the heat transfer between the nodes representing the internal and external surfaces.

Models are formulated using the discrete time state–space representation. In the linear case as in (1) and (2), developed from [52].

$$\dot{\boldsymbol{x}}(k) = \boldsymbol{A}(\boldsymbol{\theta}(k))\boldsymbol{x}(k) + \boldsymbol{B}(\boldsymbol{\theta}(k))\boldsymbol{u}(k) \tag{1}$$

$$\boldsymbol{y}(k) = \boldsymbol{C}\boldsymbol{x}(k) \tag{2}$$

Equation (1) is the result of the thermodynamic analysis of the TCL, which leads to a system of as many first-order differential equations as there are energy storage elements in the model (thermal capacities). As for the output Equation (2), it can be observed that it is not dynamic and is decided by the designer, usually with an output vector $\boldsymbol{y}(t)$ with as many coordinates as variables of interest that can be measured.

In detail, k is the sampling, $\boldsymbol{x} \in \mathbb{R}^n$ is the state vector, n the order of the model (the number of first-order differential Equations), $\boldsymbol{u} \in \mathbb{R}^p$ is the input vector, where p is the number of inputs, $\boldsymbol{A} \in \mathbb{R}^{n\times n}$ is the state matrix, $\boldsymbol{B} \in \mathbb{R}^{n\times p}$ the input matrix, and $\boldsymbol{\theta}(k) \in \mathbb{R}^m$ the vector of m model parameters. Note that the parameter vector $\boldsymbol{\theta}(k)$ depends on discrete time k because the TCL conditions can vary with time, for example, an open/closed window or open/closed refrigerator door (please, see Appendix A).

As for the output Equation (2), $\boldsymbol{y} \in \mathbb{R}^q$ is the output vector, where q is the number of outputs, and $\boldsymbol{C} \in \mathbb{R}^{q\times n}$ is the output matrix.

Next, based on the physical principles established so far, the state–space models for each TCL included in the proposed SBET will be developed.

2.1.1. Electric Space Heating/Cooling

The development of this model is based on [50]. The state, input, and output vectors of the model are written, respectively, in Equation (3).

$$\begin{aligned} \boldsymbol{x}(k)^T &= [T_{in}(k)T_{ex}(k)T_{ia}(k)] \\ \boldsymbol{u}(k)^T &= [T_{ea}(k)P_{h/c}(k)I(k)] \\ \boldsymbol{y}(k)^T &= [T_{in}(k)T_e(k)T_{ia}(k)] \end{aligned} \tag{3}$$

where the state vector $\boldsymbol{x}(k)$ is made up by the temperature at each thermal node due to the corresponding thermal capacity, three in this case: the interior building wall temperature $T_{in}(k)$, the exterior building wall temperature $T_{ex}(k)$, and the indoor air temperature or interior ambient temperature $T_{ia}(k)$, due, respectively, to the thermal capacities C_{in}, C_{ex} and C_{ia}. This model considers the interior ambient temperature as a separate temperature node $T_{ia}(k)$ of the interior building wall temperature node $T_{in}(k)$, which adds accuracy to the model because, in general, the ambient temperature and the wall temperature are different. Regarding the input vector $\boldsymbol{u}(k)$, it is made up of the variables that force temperature changes in the building. These are the outside building air temperature or exterior ambient temperature $T_{ea}(k)$ (this model considers the exterior ambient temperature different from the exterior building wall temperature $T_{ex}(k)$ since, in general, both are different, adding accuracy to the model) that influences by the wall thermal conduction and the opening of doors and/or windows, electrical power consumed by the building for heating/cooling $P_{h/c}(k)$ and irradiance $I(k)$, or energy per unit area of global solar radiation incident on a horizontal surface of the building. It is calculated according to the position and orientation of the building, as well as its geographical location (latitude and longitude) [53]. Finally, the output vector $\boldsymbol{y}(k)$ coincides with the state vector (this facilitates the use of the state vector for controller design because all its coordinates can be measured [54]) and represents the evolution of the temperatures of each of the thermal nodes. The model matrices are Equations (4)–(6).

$$\boldsymbol{A}(k) = \begin{bmatrix} -\frac{1}{R_{in,ia}C_{in}} & 0 & \frac{1}{R_{in,ia}C_{in}} \\ 0 & -\frac{1}{R_{ia,ex}C_{ex}} - \frac{1}{R_{ex,ea}C_{ex}} & \frac{1}{R_{ia,ex}C_{ex}} \\ \frac{1}{R_{in,ia}C_{ia}} & \frac{1}{R_{ia,e}C_{ia}} & -\frac{1}{R_{in,ia}C_{ia}} - \frac{1}{R_{ia,ex}C_{ia}} - \frac{1}{R_{ia,ea}(k)C_{ia}} \end{bmatrix} \tag{4}$$

$$\boldsymbol{B}(k) = \begin{bmatrix} 0 & \frac{1}{C_{in}} & \frac{0.182}{C_{in}} \\ \frac{1}{R_{ex,ea}C_{ex}} & 0 & \frac{0.05}{R_{ex,ea}C_{ex}} \\ \frac{1}{R_{ia,ea}(k)C_{ia}} & 0 & \frac{0.018}{C_{ia}} \end{bmatrix} \tag{5}$$

$$\boldsymbol{C} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{6}$$

where $R_{in,ia}$, $R_{ia,ex}$, $R_{ex,ea}$ and $R_{ia,ea}(k)$ are, respectively, the thermal resistances between nodes T_{in} and T_{ia}, T_{ia} and T_{ex}, T_{ex} and T_{ea}, T_{ia} and T_{ea}. Thus, following Equations (1) and (2), $\boldsymbol{\theta}(k) = [R_{in,ia}, R_{ia,ex}, R_{ex,ea}, R_{ia,ea}(k), C_{in}, C_{ex}, C_{ia}]$; values of these model parameters are listed in Table A1 of Appendix A. Finally, numerical values (0.182, 0.05 and 0.018) can be observed in matrix B, whose meanings are coefficients to fit the model.

The RC model for the electric space heating/cooling is shown in Figure 1. It helps to visually understand the placement and relationship between the variables present in Equations (3)–(6).

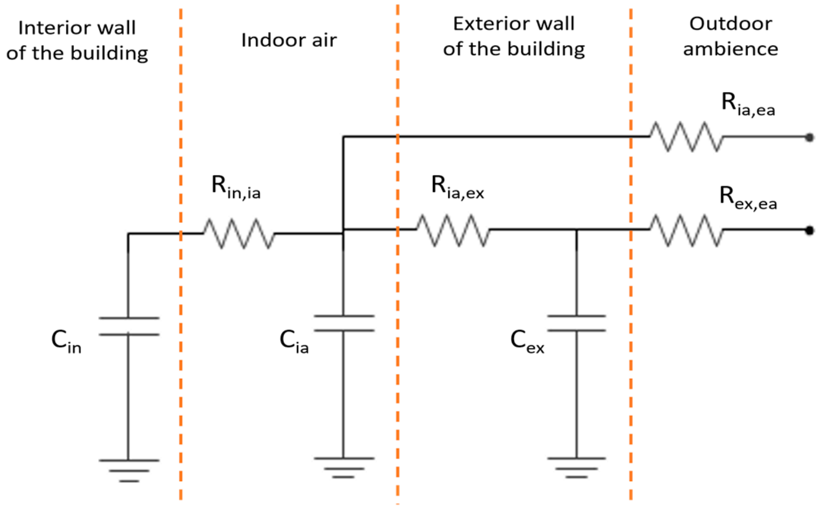


Figure 1. RC model for electric room heating/cooling.

In what follows, the meaning of the subscripts of the variables is the same for the rest of models, taking into account in each case the physical environment of each TCL.

2.1.2. Refrigerator

The development of this model is based on [55]. The state, input, and output vectors of the model are written, respectively, in Equation (7).

$$\begin{aligned} \boldsymbol{x}(k)^T &= [T_{in}(k)T_{ex}(k)] \\ \boldsymbol{u}(k)^T &= \left[T_{ia}(k)P_{ref}(k)\right] \\ \boldsymbol{y}(k)^T &= [T_{in}(k)T_{ex}(k)] \end{aligned} \tag{7}$$

where the state vector $\boldsymbol{x}(k)$ is made up by the interior refrigerator temperature $T_{in}(k)$ and the exterior temperature of the refrigerator housing $T_{ex}(k)$, due, respectively, to the thermal capacities C_{in} and C_{ex}. In this case, due to the interior volume of the refrigerator housing (considerably lesser than that of a room in a building) and its degree of thermal insulation (considerable larger than that of a room in a building) both the interior ambient temperature and the temperature of its interior walls are considered to be the same, $T_{in}(k)$. As for the input vector $\boldsymbol{u}(k)$, it is made up by the variables that force the temperature changes of the refrigerator: air temperature around the refrigerator, i.e., the interior ambient temperature of the building $T_{ia}(k)$ (this model considers the exterior ambient temperature around the refrigerator housing $T_{ia}(k)$ different from the exterior temperature of the cooler housing $T_{ex}(k)$ since in general, both are different; this adds accuracy to the model) that influences by the refrigerator housing thermal conduction and the opening of its door, and the electrical power consumed for cooling $P_{ref}(k)$. Finally, the output vector $\boldsymbol{y}(k)$ coincides with the state vector and represents the evolution of the temperatures of each of the thermal nodes. The model matrices are Equations (8)–(10).

$$\boldsymbol{A}(k) = \begin{bmatrix} -\frac{1}{R_{in,e}C_{in}} - \frac{1}{R_{in,ia}(k)C_{in}} & \frac{1}{R_{in,ex}C_{in}} \\ \frac{1}{R_{in,e}C_{ex}} & -\frac{1}{R_{in,ex}C_{ex}} - \frac{1}{R_{e,ia}C_{ex}} \end{bmatrix} \tag{8}$$

$$\boldsymbol{B}(k) = \begin{bmatrix} \frac{1}{R_{in,ia}(k)C_{in}} & -\frac{1}{C_{in}} \\ \frac{1}{R_{ex,ia}C_{ex}} & 0 \end{bmatrix} \tag{9}$$

$$\boldsymbol{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{10}$$

where $R_{in,ex}$, $R_{in,ia}(k)$, and $R_{ex,ia}$ are, respectively, the thermal resistances between nodes T_{in} and T_{ex}, T_{in} and T_{ia}, T_{ex} and T_{ia}. Thus, following Equations (1) and (2), $\boldsymbol{\theta}(k) = [R_{in,ex}, R_{in,ia}(k), R_{ex,ia}, C_{in}, C_{ex}]$; values of these model parameters are listed in Table A2 of Appendix A.

The RC model for the refrigerator is shown in Figure 2. It helps to visually understand the placement and relationship between the variables present in Equations (7)–(10).

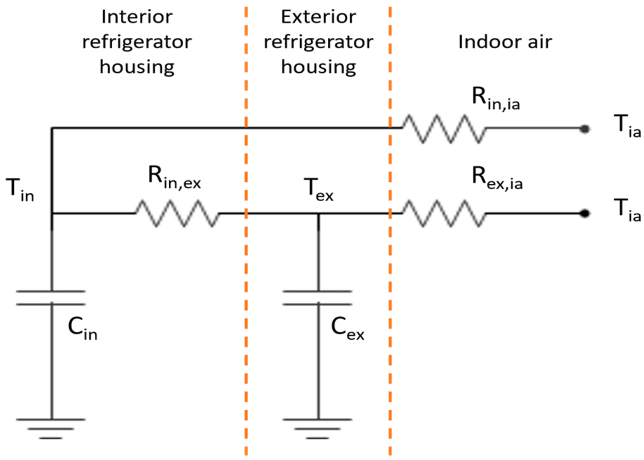


Figure 2. RC model for the refrigerator, freezer, and electric water heater.

2.1.3. Freezer

Following [56], the model of the freezer is analogous to that of the refrigerator, i.e., Equations (7)–(10). Power consumed for cooling is $P_{fre}(k)$. Model parameters values are listed in Table A3 of Appendix A.

The RC model for the freezer is also shown in Figure 2.

2.1.4. Electric Water Heater

The development of this model is based on [57]. The state, input, and output vectors of the model are written, respectively, in Equation (11).

$$\begin{aligned} \boldsymbol{x}(k)^T &= [T_{inw}(k) T_{ex}(k)] \\ \boldsymbol{u}(k)^T &= [T_{suw}(k) P_{heater}(k)] \\ \boldsymbol{y}(k)^T &= [T_{inw}(k) T_{ex}(k)] \end{aligned} \tag{11}$$

where the state vector $\boldsymbol{x}(k)$ is made up by the interior water temperature of the heater $T_{inw}(k)$ and the exterior temperature of the water heater housing $T_{ex}(k)$, due, respectively, to the thermal capacities C_{inw} and C_{ex}. As for the input vector $\boldsymbol{u}(k)$, it is made up of the variables that force the temperature changes of the water in the heater: temperature of cold water supplied to the heater $T_{suw}(k)$ (when the water heater is receiving water from outside to compensate for the water it is supplying) and the electrical power consumed for heating $P_{heater}(k)$. Faced with these input coordinates with a great influence on the changes in water temperature in the heater, thermal conduction of the heater housing is not taken into account (the water heater will normally be inside a cabinet and the heat exchange with the outside can be considered negligible compared to the daily inflow of cold water). Again, the output vector $\boldsymbol{y}(k)$ coincides with the state vector and represents the evolution of the temperatures of each of the thermal nodes.

Changing the corresponding subscripts and values, matrix $\boldsymbol{A}$ is the same as in Equation (8), matrix $\boldsymbol{B}$ is the same as in Equation (9), and matrix $\boldsymbol{C}$ is the same as in Equation (10). Model parameters values are listed in Table A4 of Appendix A.

The RC model for the electric water heater is the same as for the refrigerator and freezer and is shown in Figure 2.

2.2. Temperature and Irradiance Measurement

As can be seen in the models of the Section 2.1, to calculate the electrical power $P(t)$ consumed by the TCLs it is necessary to have continuously available interior and exterior ambient temperatures to the building, interior and exterior wall temperatures, as well as the irradiance to which the building is exposed. In addition, for the refrigerator and freezer, it is necessary to know the internal and external temperatures of their housings. Finally, as far as the electric water heater is concerned, it is necessary to know the temperature of the water inside it and the inlet temperature coming from the supply to the building.

In general, obtaining temperature values is very simple, since it is enough to have thermometers for this purpose (many household appliances supply them directly; [58] is a very accurate and inexpensive device for measuring surface temperatures as in [59]), and even the ambient air temperature outside the building can be obtained directly from the weather stations available in all cities (in the larges there are usually different measurement points, which logically allows it to choose the closest one). The same applies to the temperature of the water stored inside the water heater (provided by the device itself). There are even water heaters that provide information on the inlet water temperature from the exterior. In any case, water supply companies provide graphs of water supply temperatures. For example, in the city of Huelva (southwestern Spain), the monthly supply temperatures for 2021 are shown in Table 1 [60].

Table 1. Water supply temperature (°C) in the city of Huelva (southwestern Spain) in 2021.

Month	Temperature
January	12
February	12
March	13
April	14
May	16
June	18
July	20
August	20
September	19
October	17
November	14
December	13

That said with respect to the ease of measuring temperatures, the same does not apply to irradiance. The device for measuring solar radiation on a flat surface (irradiance) is called a pyranometer. It is an expensive meter that, in addition, requires special care in positioning for reliable measurements. Therefore, it is not easy, much less usual, for every building to have one. For this reason, the developed SBET-TCLs calculates the irradiance instead of measuring it, for which Equation (12) is used, which was adapted from [61].

$$I\left(t_f - t_0\right) = K\cdot e\cdot\left(12/\,\pi\right)\left(\sin(\varphi)\cdot\sin(\theta)\cdot\left(\varnothing_{sf} - \varnothing_{s0}\right) + \cos\,(]\varphi)\cdot\cos\,(\theta)\cdot\left(\sin\varnothing_{sf} - \sin\varnothing_{s0}\right)\right) \tag{12}$$

where:

$I\left(t_f - t_0\right)$ is the received irradiance in $\mathrm{W/m^2}$ between the initial time t_0 and the final time t_f considered;

K is the solar constant or total solar irradiance, i.e., the total amount of energy received as solar radiation per unit time and area measured outside the Earth's atmosphere in a perpendicular plane to the sun's rays. The measured and accepted value is 1361 $\mathrm{W/m^2}$;

e is the correction factor of K due to the eccentricity of the Earth's orbit around the sun [62]. Specifically, $e = 1 + 0.033\cdot\cos(2\pi n/365)$, where n is the number of days between 1 (January 1) and 365 (December 31);

φ is the latitude of the building under study;

θ is the solar declination resulting from the tilt of the Earth's rotation axis. The value of solar declination varies continuously throughout the year, from a maximum of $+\theta$ at the boreal summer (austral winter) solstice to a minimum of $-\theta$ at the boreal winter (austral summer) solstice, where θ is the obliquity of the ecliptic. Solar declination is zero at the spring and autumnal equinoxes. $\theta = 23.45° \cdot (\pi/180°) \cdot \sin(2\pi((284 + n)/365))$;

$\varnothing_s$ is the solar angle, 0 at noon, negative in the mornings, and with a variation of 15° per hour from noon on. Then, between t_0 and t_f varies between $\varnothing_{s0}$ and $\varnothing_{sf}$, respectively. Finally, n is the number of days between 1 (January 1) and 365 (December 31).

2.3. Educational Framework of the Developed Simulation-Based Educational Tool

The study involved undergraduate engineering students in the subject 'Alternative Energy Sources'. In this subject, students learn about the most commonly used renewable energy sources and energy demand management. Within this last topic, the concepts and applications of TCLs are presented. Therefore, the common TCLs in a building are identified, i.e., electric space heating/cooling, refrigerators, freezers, and electric water heaters, and then their dynamic thermal models are studied, as well as the most commonly used control methods. The TCL topic is taught over three weeks, two of which focus on theoretical concepts and the last on student work with the tool. In this way, they can see the effect of the different parameters of the models on the behavior of the TCLs and confirm the theoretical concepts taught in previous weeks.

Until the introduction of the proposed SBET-TCLs, teachers taught the TCL framework in a theoretical way, and there was no measure of student's learning in this scope other than theoretical assessment. In this regard, the assessment consisted of a written test.

To measure the suitability as an educational resource of the proposed SBET-TCLs, students were asked to fill out a questionnaire with a set of questions on a 5-point Likert scale (1 = strongly disagree and 5 = strongly agree). The questionnaire was organized in different sections, focusing on the students' level of knowledge of the subject, and on computer simulation-based learning, as well as on aspects of acceptance, design and usability of the simulation tool together with general considerations. Table 2 shows the survey questionnaire. To conduct this survey, a total of 48 students of the subject 'Alternative Energy Sources' (fourth-year elective) from the undergraduate degrees in Electrical Engineering (21% of students), Industrial Electronic Engineering (21%), Mechanical Engineering (29%), and Industrial Chemical Engineering (29%) of the University of Huelva were asked. The study was carried out in the second semester of the 2021–2022 academic year. The questions listed in Table 2 were asked to the students during laboratory sessions, when the teacher was already aware that they had understood the necessary theoretical concepts about the TCLs.

Table 2. Summary of survey.

Section	Question	Description
Students' background	1	Your level in 'Energy Efficiency' is high
SBET-TCLs experience	2	The simulation tool allows for the consolidation of theoretical concepts
	3	Theoretical concepts can be learned only through theoretical study
	4	Computer simulation facilitates theoretical and practical understanding
	5	Learning is more engaging through the use of the simulation tool
Acceptance of use	6	The simulation tool should be used in undergraduate engineering degrees

Table 2. *Cont.*

Section	Question	Description
Design quality and ease of use	7 8	The interface is friendly The simulation tool is easy to use
Overall assessment	9	The overall assessment of the simulation tool is positive

3. Developed Simulation-Based Education Tool

In the following, the developed SBET-TCLs will be explained, both its internal structure and its interface and capabilities.

Figure 3 shows the interface that the student can see when accessing the tool through an XHTML page. The interface is very simple, intuitive, and easy to use. The student must enter the data and parameters corresponding to the desired simulation. Specifically, in the first line: the corresponding date (day, month and year) and the start time (hour, minute and second). In the example in Figure 3, 3 January 2021, 10 s after midnight.

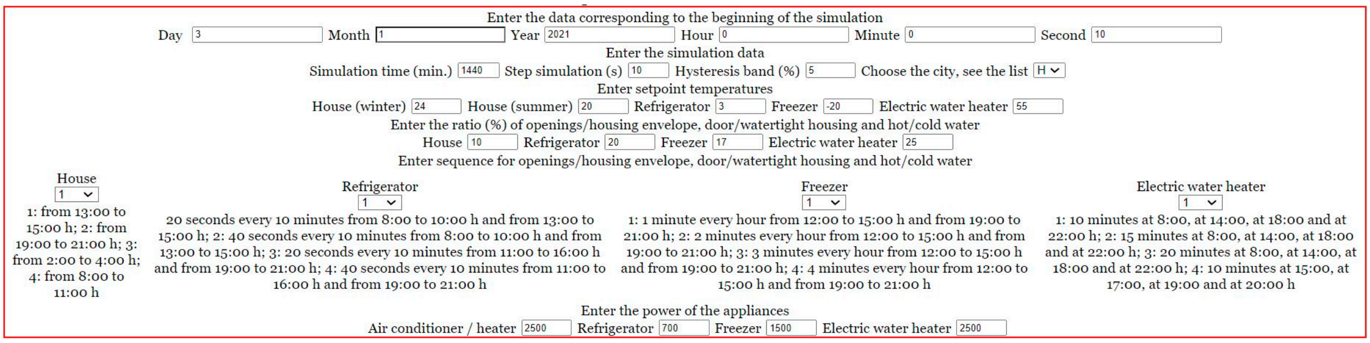


Figure 3. Interface of the simulation-based education tool for thermostatically controlled loads.

In the second line, the simulation data must be entered: simulation time in minutes, step simulation in seconds, hysteresis band percentage (this is a percentage of the set point temperatures, i.e., in a real situation, it prevents the respective thermostats of the appliances from switching on and off continuously), and the city where the building is. In the example shown in Figure 3 and by the same order: 1440 min (24 h), samples every 10 s, allowable percentage of 5% temperature variation from the set point temperature and, finally, the city of Huelva (southern Spain) for the location of the building.

The third line includes the set points for the temperatures (°C) of the different TCLs, i.e., the winter and summer comfort temperatures in the building, as well as the refrigerator, freezer and electric water heater. In the example shown in Figure 3 and by the same order: 24 °C (this means that with the chosen hysteresis band (5%), and taking into account that it is a winter day, the interior temperature of the building can drop up to 22.8 without activating the electric space heating; of course, the same applies to all other set point temperatures listed below), 20 °C, 3 °C, −20 °C, and 55 °C.

The fourth line allows to take into account the variation of the thermal resistances due to the opening of doors and/or windows (building), doors (refrigerator and freezer), and the contact of the incoming cold water with the internal hot water each time the electric water heater is used (outgoing hot water is replenished with incoming cold water). The meaning of the ratio (%) of openings/housing envelope, door/watertight housing and hot/cold water is as follows in each case: surface area of the open doors and/or windows in relation to the surface area of the envelope of the building, surface of the open door in relation to the refrigerator and freezer watertight housing and, finally, in the case of the electric water heater is the percentage of stored hot water consumed in each use. In the example shown in Figure 3 and by the same order: 10% (sum of the doors and/or windows) of the total envelope of the dwelling is open to the exterior, 20% (the surface of the refrigerator door is one-fifth of its total watertight enclosure), analogous to the freezer but now only 17% and, finally, 25% means that for each shower, one-quarter of the total hot water stored in the electric water heater is used and, subsequently, replaced by cold water.

The user can decide on the fifth line at what times and for how long the doors and windows of the building, the refrigerator and freezer door will be open, as well as how the water heater will be used. Of course, as for the use of the appliances, the casuistry can be infinite, so the tool offers only some representative options. In fact, what is really intended is that the student learns to know how the different types of uses affect consumption so that he/she can apply responsible use. In the example shown in Figure 3 the sequence is 1-1-1-1.

Finally, the last line of the interface allows to introduce the power (W) of the appliances that represent the TCLs; in the case of Figure 3: air conditioner/heater (2500 W), fridge (700 W), freezer (1500 W) and water heater (2500 W).

The developed SBET-TCL was implemented by Easy Java Simulations (EJS) [48], an open-source tool written in Java, mainly for teaching and learning purposes. During the last decade, EJS has been widely used in educational research in engineering, specifically in automatic control [63], robotics [64] and automation [65] among others. Moreover, after years of implementation and use of remote laboratories in higher engineering studies, the authors of this work have already achieved sufficient experience with this tool.

As for the structure of the developed SBET-TCL, it is shown in Figure 4 and will be explained below. First, the tool loads the data entered by the user through the interface of Figure 3. Then loads the models with their parameters (Section 2.1 and Appendix A, Tables A1–A4). To these, the temperature data are added. From here, the irradiance is calculated by Equation (12). Now, once the models have been updated, the consumed power by each TCL can be calculated. In this sense, the algorithm takes into account the hysteresis band selected by the user, as well as the setpoint temperature of each TCL. If this is within the hysteresis band, the corresponding TCL does not consume power.

The algorithm runs in a loop until the end of the simulation time (t_f) chosen by the user in the interface (Figure 3). Note that temperatures should be updated at each sampling. The same is true for the model parameters, which will be updated depending on the user's choice (Figure 3) of the sequence for openings/housing envelope, door/watertight housing and hot/cold water. For that, the algorithm loads the proper data (please see Appendix A, Tables A1–A4) of $R_{ia,ea}$, $R_{in,ia}$ and $R_{inw,suw}$. When the algorithm goes out of the loop, the chosen simulation time has finished and the integration of the power over the simulation time delivers the energy consumed. As will be seen in the following section on results, the SBET-TCL provides a set of graphs and tables that allow a detailed analysis of consumption.

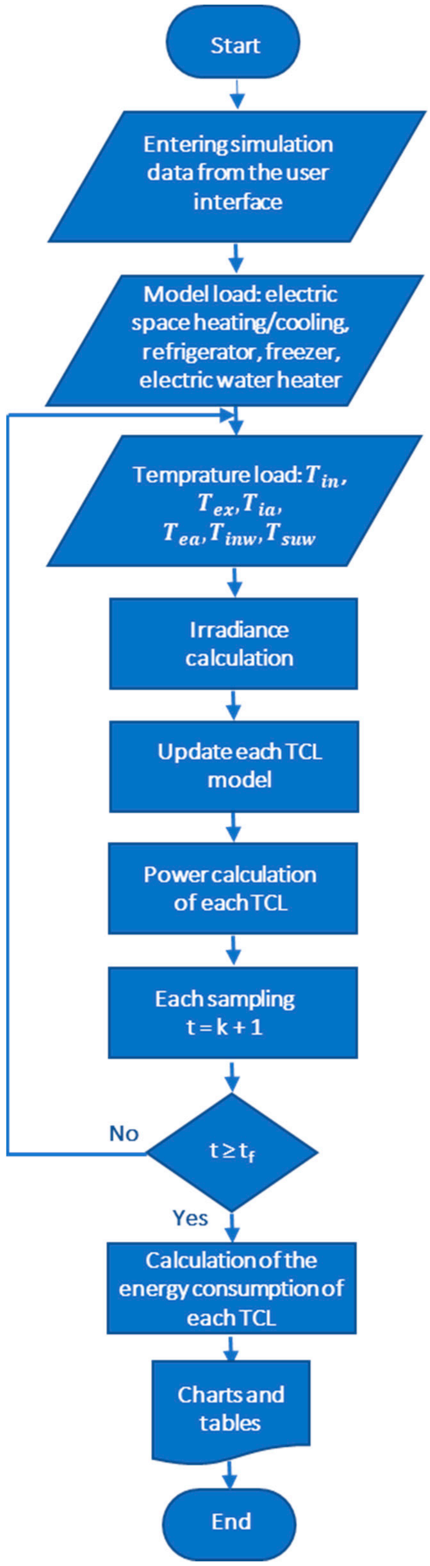


Figure 4. Flow chart of the developed SBET-TCLs.

4. Results

In this work, the results are of two types, namely, those from the technical performance of the developed SBET-TCLs and those corresponding to the evaluation of the SBET as an educational resource.

4.1. Technical Performance of the Developed SBET-TCLs

In order to obtain sufficient variability when displaying the results of the developed SBET-TCLs, a winter day and a summer day were chosen. For both, two different sequences (1–1–1–1 and 2–4–3–3) for openings/housing envelope, door/watertight housing, and hot/cold water (please, see Figure 3) were taken into account. A total of four simulations were carried out.

The following figures (Figures 5–17) show the behavior of the appliances regarding the interface set by the user and the environmental conditions of the dwelling. In the figures mentioned above, the indoor and outdoor temperatures are shown in blue and green, respectively, and the activation of the thermostat of each device and, consequently, the power consumption (always considering the nominal one), are in black.

Day: 3 January 2021. Sequence: 1–1–1–1. Its interface corresponds to that shown in Figure 3. Results are shown in Figures 5–7.

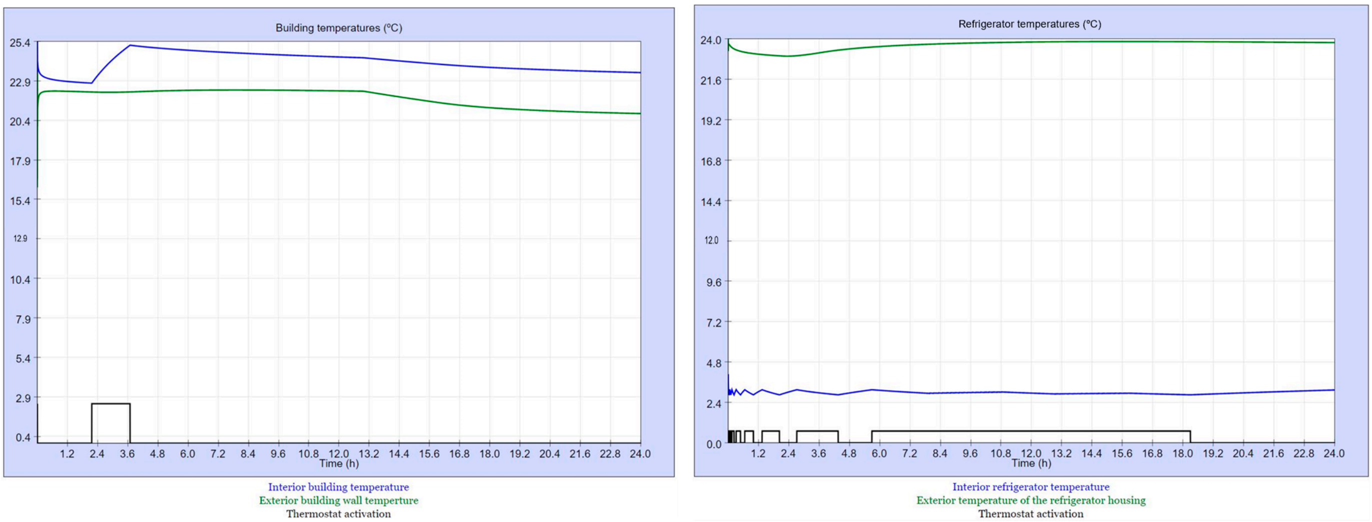


Figure 5. Date: 3 January 2021. Sequence: 1–1–1–1. Behavior of the space heating/cooling (**left**) and refrigerator (**right**).

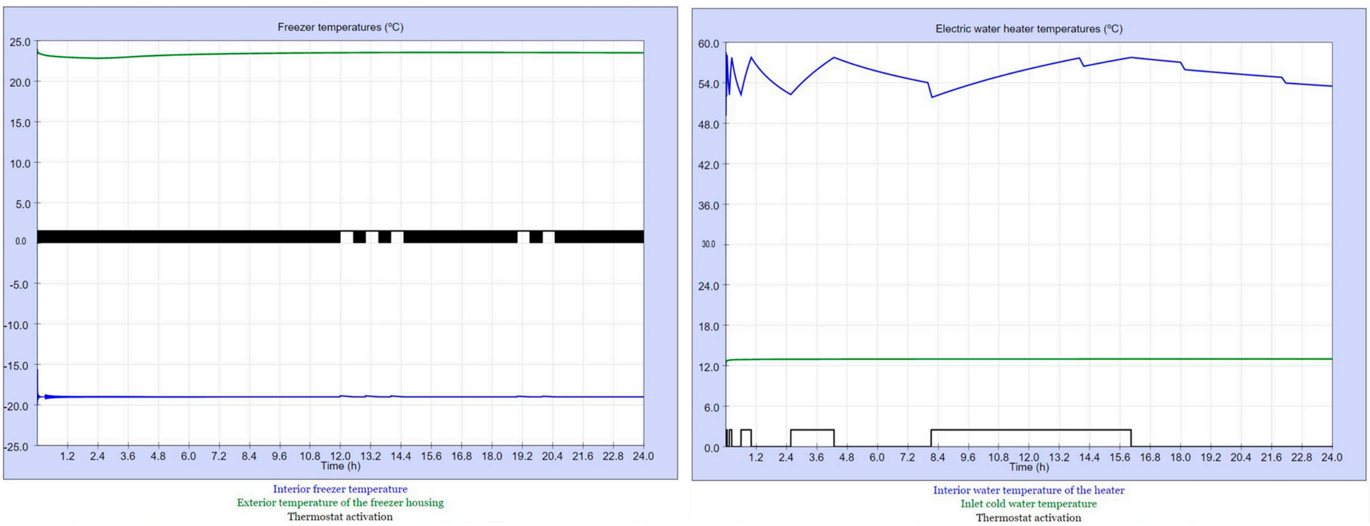


Figure 6. Date: 3 January 2021. Sequence: 1–1–1–1. Behavior of the freezer (**left**), electric water heater (**right**), and daily consumption (**down**).

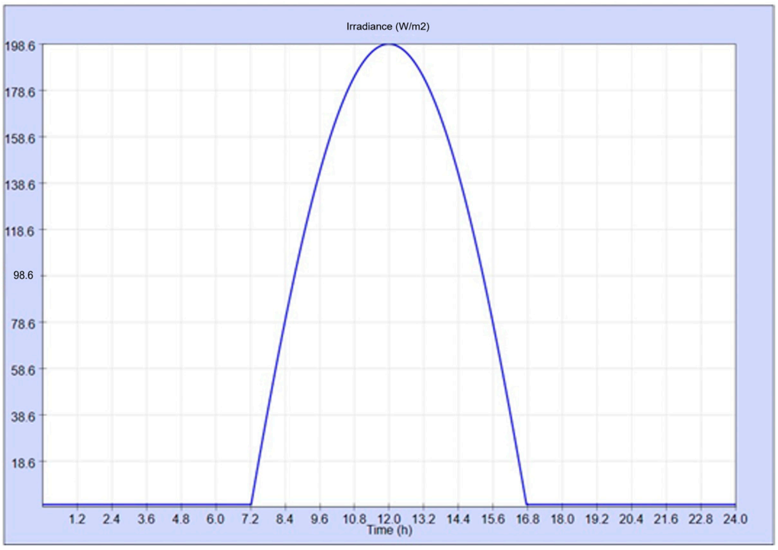
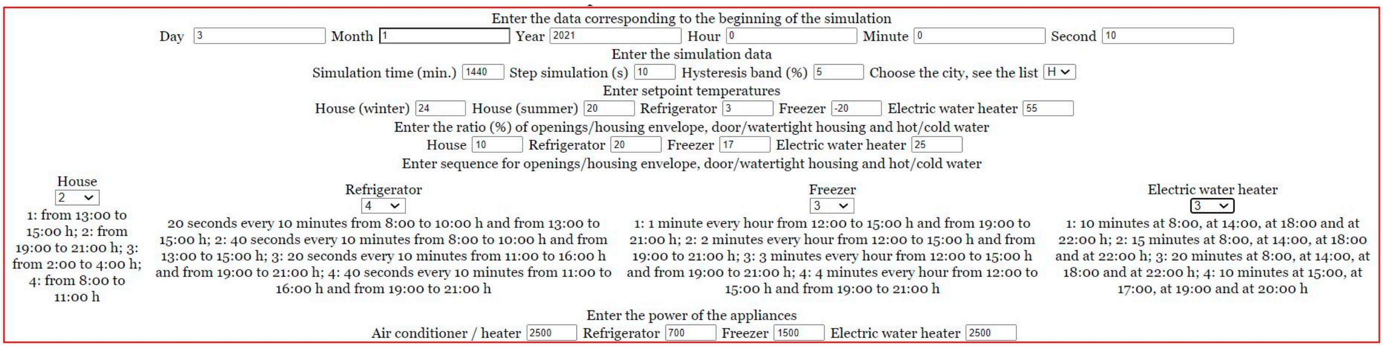


Figure 7. Date: 3 January 2021. Daily irradiance.

Day: 3 January 2021. Sequence: 2–4–3–3. Its interface corresponds to that shown in Figure 8. Results are shown in Figures 9 and 10. Of course, the daily irradiance is that of Figure 7.


Enter the data corresponding to the beginning of the simulation
Day 3 Month 1 Year 2021 Hour 0 Minute 0 Second 10
Enter the simulation data
Simulation time (min.) 1440 Step simulation (s) 10 Hysteresis band (%) 5 Choose the city, see the list H
Enter setpoint temperatures
House (winter) 24 House (summer) 20 Refrigerator 3 Freezer -20 Electric water heater 55
Enter the ratio (%) of openings/housing envelope, door/watertight housing and hot/cold water
House 10 Refrigerator 20 Freezer 17 Electric water heater 25
Enter sequence for openings/housing envelope, door/watertight housing and hot/cold water

House 2
1: from 13:00 to 15:00 h; 2: from 19:00 to 21:00 h; 3: from 2:00 to 4:00 h; 4: from 8:00 to 11:00 h

Refrigerator 4
20 seconds every 10 minutes from 8:00 to 10:00 h and from 13:00 to 15:00 h; 2: 40 seconds every 10 minutes from 8:00 to 10:00 h and from 13:00 to 15:00 h; 3: 20 seconds every 10 minutes from 11:00 to 16:00 h and from 19:00 to 21:00 h; 4: 40 seconds every 10 minutes from 11:00 to 16:00 h and from 19:00 to 21:00 h

Freezer 3
1: 1 minute every hour from 12:00 to 15:00 h and from 19:00 to 21:00 h; 2: 2 minutes every hour from 12:00 to 15:00 h and from 19:00 to 21:00 h; 3: 3 minutes every hour from 12:00 to 15:00 h and from 19:00 to 21:00 h; 4: 4 minutes every hour from 12:00 to 15:00 h and from 19:00 to 21:00 h

Electric water heater 3
1: 10 minutes at 8:00, at 14:00, at 18:00 and at 22:00 h; 2: 15 minutes at 8:00, at 14:00, at 18:00 and at 22:00 h; 3: 20 minutes at 8:00, at 14:00, at 18:00 and at 22:00 h; 4: 10 minutes at 15:00, at 17:00, at 19:00 and at 20:00 h

Enter the power of the appliances
Air conditioner / heater 2500 Refrigerator 700 Freezer 1500 Electric water heater 2500

Figure 8. Date: 3 January 2021. Sequence: 2–4–3–3. Interface of the simulation-based education tool.

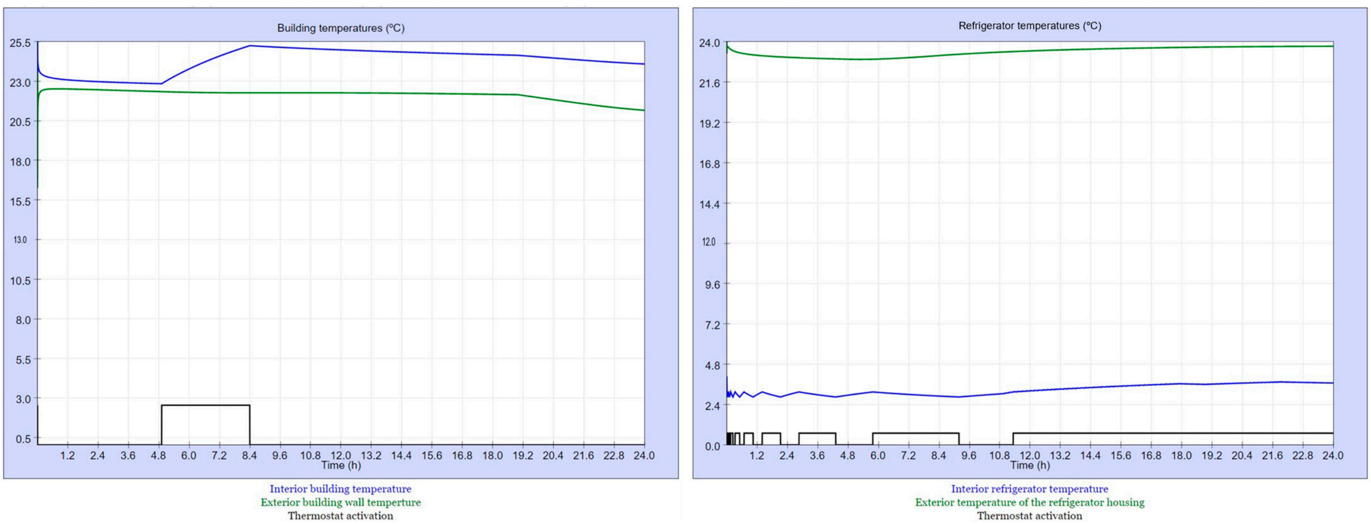


Figure 9. Date: 3 January 2021. Sequence: 2–4–3–3. Behavior of the space heating/cooling (**left**) and refrigerator (**right**).

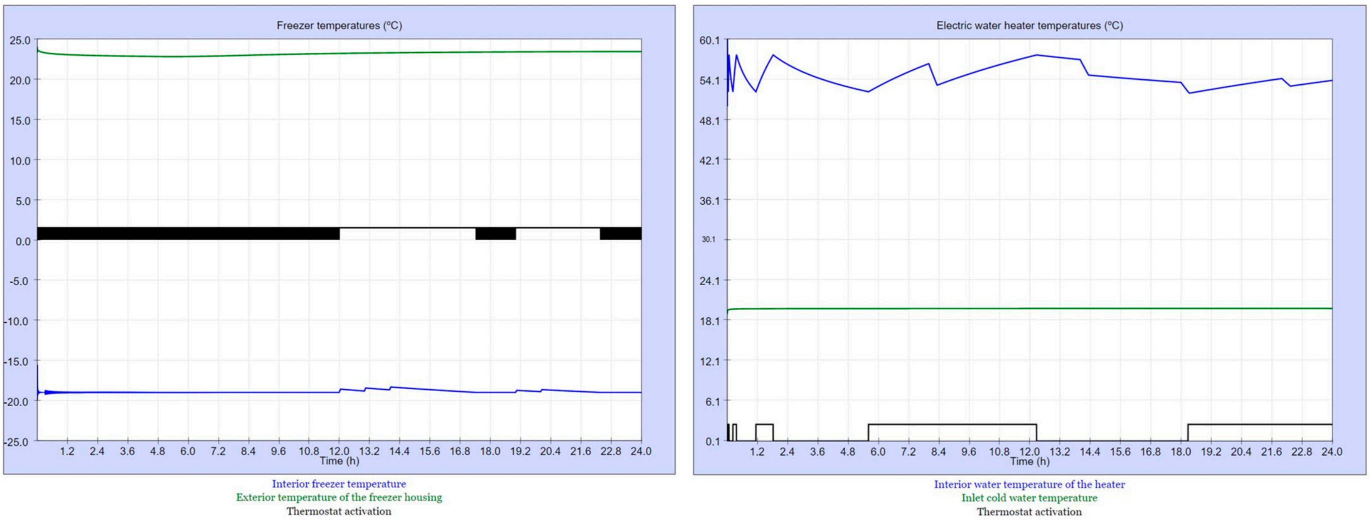


Figure 10. Date: 3 January 2021. Sequence: 2–4–3–3. Behavior of the freezer (**left**), electric water heater (**right**) and daily consumption (**down**).

Day: 3 July 2021. Sequence: 1–1–1–1. Its interface corresponds to that shown in Figure 11. Results are shown in Figures 12–14.

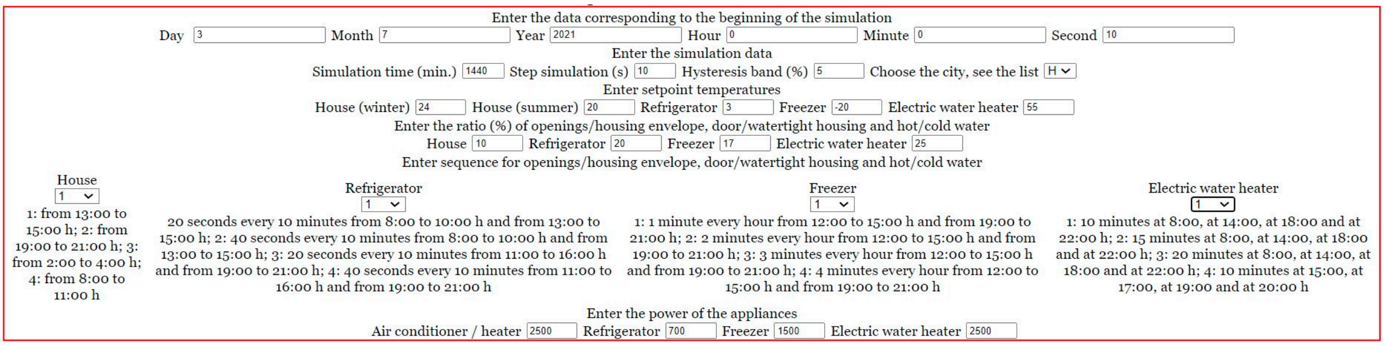


Figure 11. Date: 3 July 2021. Sequence: 1–1–1–1. Interface of the simulation-based education tool.

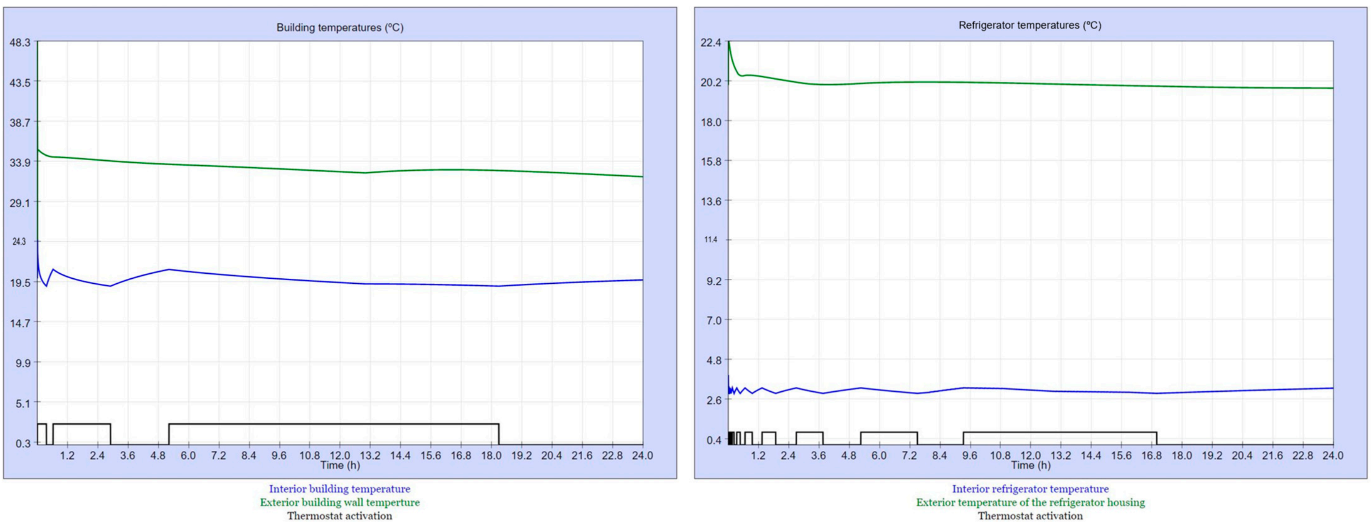


Figure 12. Date: 3 July 2021. Sequence: 1–1–1–1. Behavior of the space heating/cooling (**left**) and refrigerator (**right**).

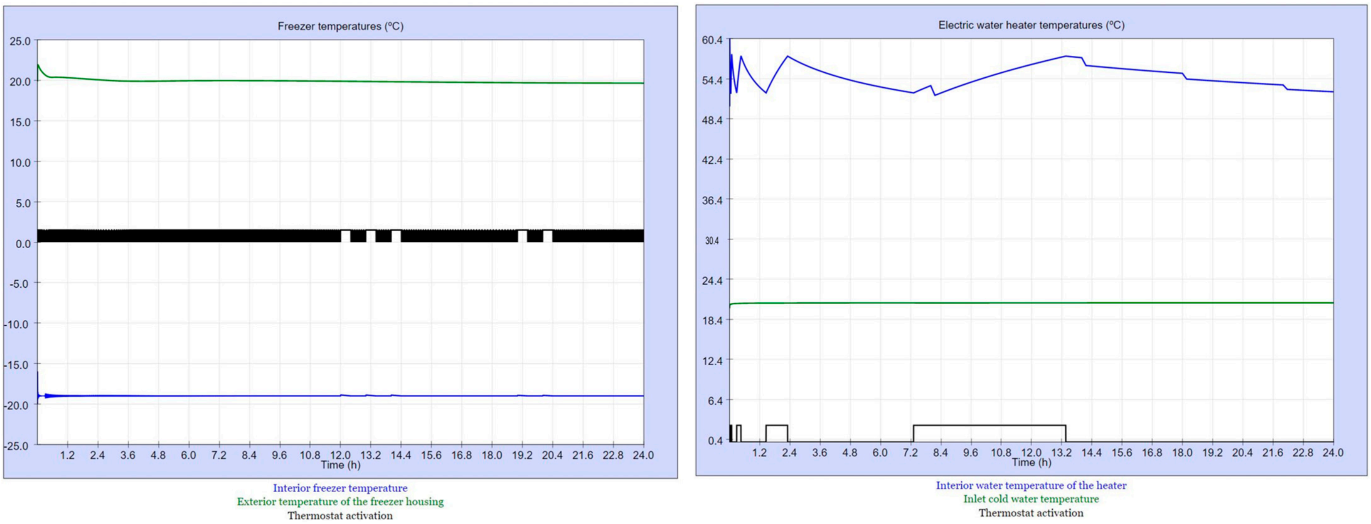


Figure 13. Date: 3 July 2021. Sequence: 1–1–1–1. Behavior of the freezer (**left**), electric water heater (**right**) and daily consumption (**down**).

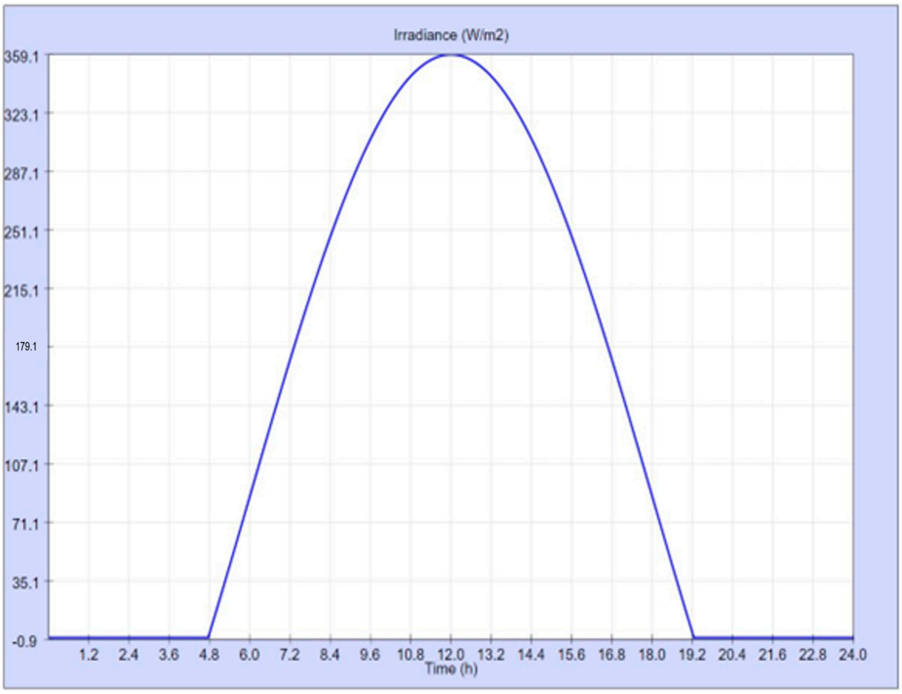


Figure 14. Date: 3 July 2021. Daily irradiance.

Day: 3 July 2021. Sequence: 2–4–3–3. Its interface corresponds to that shown in Figure 15. Results are shown in Figures 16 and 17. Of course, the irradiance is that of Figure 14.

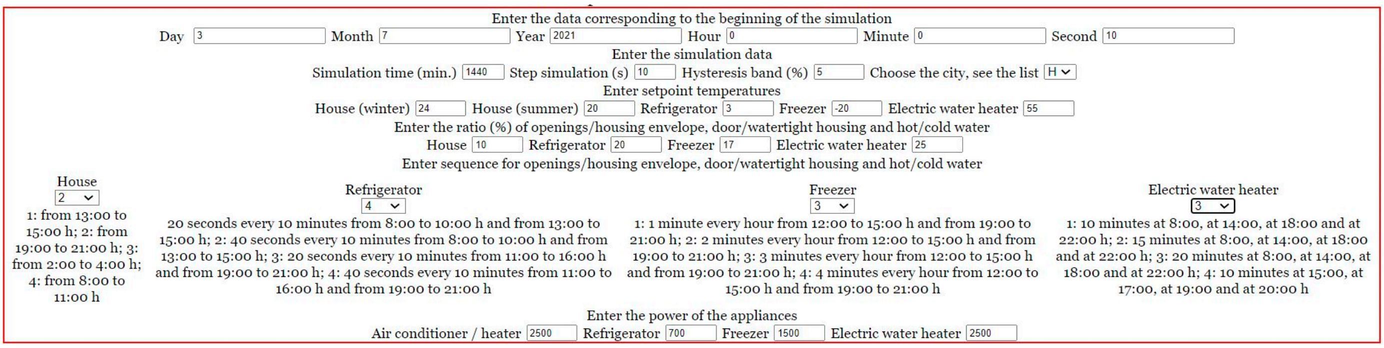


Figure 15. Date: 3 July 2021. Sequence: 2–4–3–3. Interface of the simulation-based education tool.

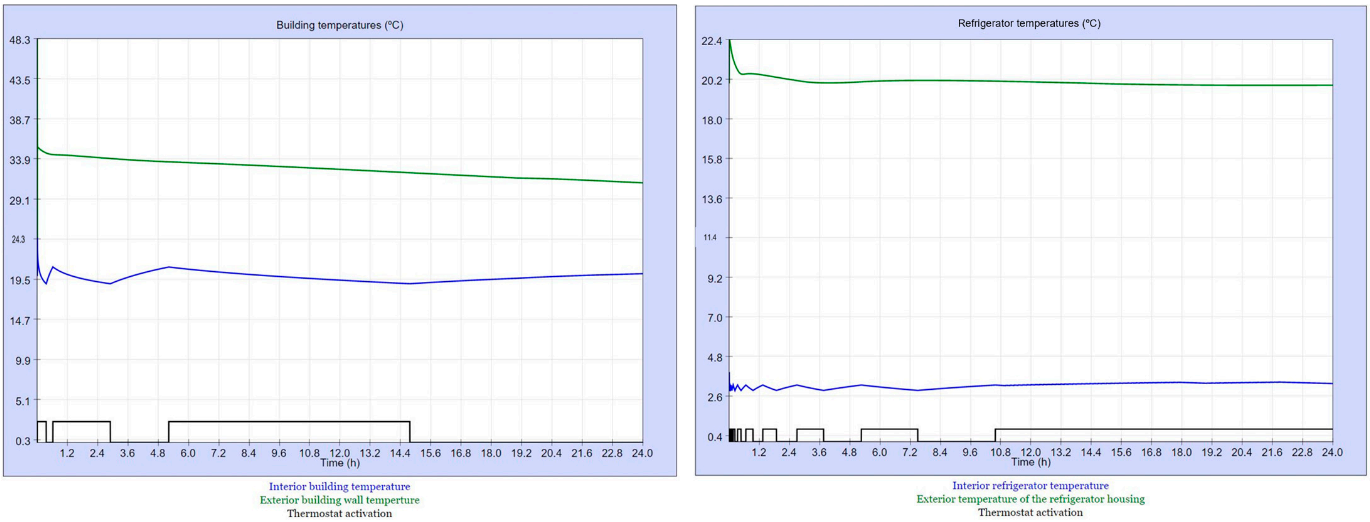


Figure 16. Date: 3 July 2021. Sequence: 2–4–3–3. Behavior of the space heating/cooling (**left**) and refrigerator (**right**).

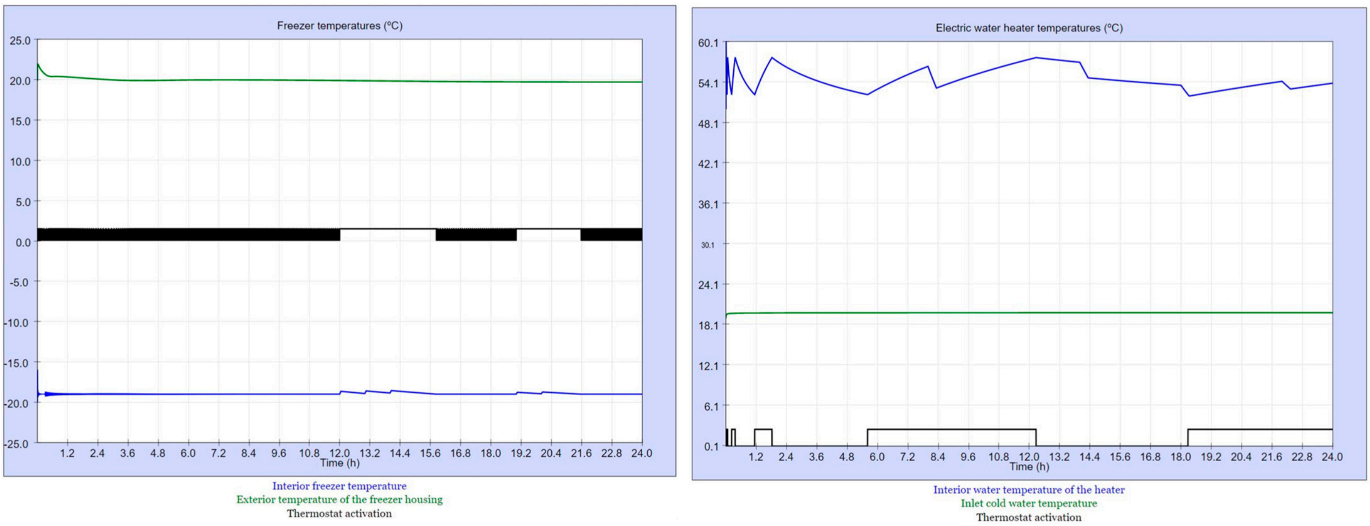


Figure 17. Date: 3 July 2021. Sequence: 2–4–3–3. Behavior of the freezer (**left**), electric water heater (**right**) and daily consumption (**down**).

Table 3 summarizes the energy consumption in each of the four scenarios considered.

Table 3. TCL consumption (kWh) as a function of the operating scenario.

TCL	Sequence	Season	TCL Consumption
Space heating/cooling	Sequence 1–1–1–1	Winter	8715
		Summer	39,250
	Sequence 2–4–3–3	Winter	8715
		Summer	36,819
Refrigerator	Sequence 1–1–1–1	Winter	11,359
		Summer	8451
	Sequence 2–4–3–3	Winter	13,277
		Summer	10,588
Freezer	Sequence 1–1–1–1	Winter	22,613
		Summer	20,242
	Sequence 2–4–3–3	Winter	26,421
		Summer	21,199
Water heater	Sequence 1–1–1–1	Winter	25,368
		Summer	17,778
	Sequence 2–4–3–3	Winter	45,285
		Summer	37,174

4.2. Evaluation of the SBET-TCL as an Educational Resource

Students in the 'Alternative Energy Sources' course have evaluated SBET-TCL in the scenarios shown in Section 4.1. Among others designed by themselves, and with the objective of making them to realize the need of controlling TCLs, the test indicated in Table 4 was proposed. As can be seen, it consists of three simulations. The first one is the base case with the parameters indicated in Figure 11, except hysteresis band. In the second one, all the parameter and kept constant except the building set point, which is increased from 24 °C to 27 °C. The parameters corresponding to the third simulation are the same as the corresponding parameters in the second one, except the hysteresis band, which was highly increased. The rest of initial parameters not included in Table 4 correspond with Figure 11. The total consumption obtained in each case is presented in Table 4.

Table 4. TCLs simulation input parameters in analyzed cases.

Simulation Parameter	Unit	Value A	Value B	Value C
Hysteresis band		0.01	0.01	0.05
Space cooling setpoint	°C	24	27	27
Fridge setpoint	°C	3	3	3
Freezer setpoint	°C	−20	−20	−20
Electric water heater setpoint	°C	55	55	55
Total consumption	kWh	96,713	95,362	80,419

Now, once checked the technical suitability of the developed tool was time to check its educational suitability. For this purpose, the survey designed in Table 2 was carried out. The result is shown in Figure 18. Q1–Q9 represent, respectively, the questions indicated in Table 2, Section 2.3.

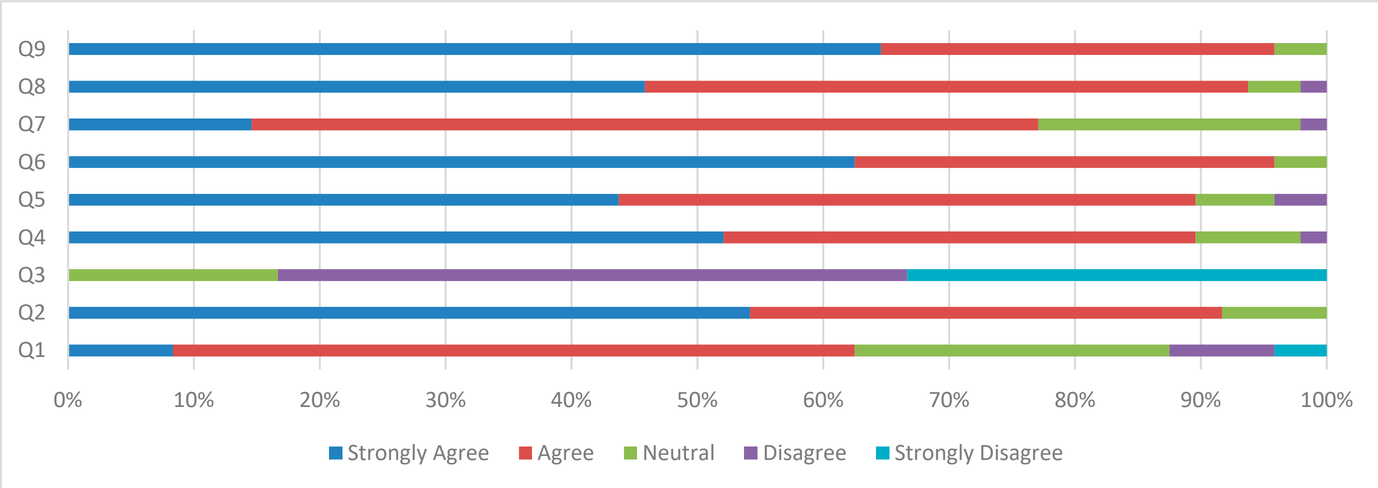


Figure 18. Evaluation questionnaire of the SBET-TCL as an educational resource.

5. Discussion

5.1. Technical Performance of the Developed SBET-TCL

The SBET-TCL developed in this work constitutes a very good tool for students of different degrees and qualifications to learn the operation of TCLs as well as the need for their control to reduce their electrical consumption. Regarding fridge and freezer, the curves representing the evolution of the different temperatures are very similar in summer and winter because their operation mainly depends on the ambient temperature in the place that they are located. Thus, their consumption is higher in winter, when the building temperature set point is higher than in summer. In addition, their consumption is higher as higher is the time involved in "openings/housing envelop, door watertight/housing and hot/cold water", i.e., the consumption corresponding to 2–4–3–3 sequence is always higher than the corresponding to 1–1–1–1.

With respect to the electric water heater, it must be observed in Table 3 that the consumption corresponding to the summer is lower that the winter. This is consequent because the inlet winter temperature is lower than the corresponding to the summer. In addition, the consumption corresponding to the 2–4–3–3 sequence is about the double of the corresponding to 1–1–1–1 as the time of using hot water in the second case is about the middle of the first.

Finally, regarding the building, the consumption is much higher in summer, as correspond to a place with a hot weather. The consumption corresponding to the sequence 2–4–3–3 is higher than that corresponding to 1–1–1–1 in summer. In winter, the consumption corresponding to the two sequences is the same, although a small difference can be seen in the curves showing the evolution of the temperatures (Figure 5 left and Figure 9 left).

The simulations, the results of which are presented in Table 4, show the students the importance of controlling the TCL parameters in order to limit their consumption. In this sense, they can observe that the electrical consumption in the third simulation had the lowest value compared to the first and second simulation. This was a consequence of increasing two key variables: the hysteresis band corresponding to all the TCLs and the room cooling setpoint.

5.2. Evaluation of the SBET-TCL as an Educational Resource

As mentioned in Section 2.3, the subject of 'Alternative Energy Sources' is taught in four industrial engineering degrees at the University of Huelva: Electrical Engineering, Electronic Engineering, Mechanical Engineering and Chemical Engineering. They all share part of their training curriculum, although the specialization varies greatly from one to the other. In electrical engineering, the specialist part of the course focused on electrical machines and installations. Electronic training focuses on electronic systems and automatic. Mechanical in structures and mechanical design, and chemical in chemical processes and petrochemical. However, all the students were enrolled in courses such as 'Thermodynamics', 'Modeling and Simulation for Engineering Systems' and 'Automation and Control for Engineering Systems', among others, as part of the joint training. Despite the diversity of the students' curricula, they all value the training in TCLs and the use of the SBET-TCL as a valuable addition to their education.

One of the aims of the subject is to teach students about energy efficiency in buildings. With the SBET-TCL, students can observe the electrical energy required by different loads in a building, as shown in Table 4. They can also look for solutions to reduce energy consumption, such as changing the setpoint, the hysteresis band or the operating scenario. This make them aware of the importance of the TCLs in an energy-efficient building approach.

Before the inclusion of SBET-TCL in the TCL topic, dynamic thermal models were studied only from a theoretical approach. Thus, first the RC model of each TCL is established, then the corresponding state–space model is obtained. However, the students were not able to experiment with the models they had developed, i.e., they did not observe their dynamics in steady state or when key variables were changed.

In order to assess the academic impact of the inclusion of SBET-TCL, the average scores achieved by students in the TCL written test in recent years were compared. Before using SBET-TCL, the average qualification was 7.0 and after using it was 8.5. Therefore, this fact allows us to affirm that the use of SBET-TCL represents a real improvement in the learning process.

Based on all the above, the SBET-TCL has enabled students from different degrees to progress in the study of TCL, to apply the theoretical concepts in a practical way, to become aware of the potential of TCL to reduce global energy consumption and CO2 emissions in buildings, and to improve their qualifications in the subject.

In addition, considering the responses to the questions, it can be said that the students gave a generally positive assessment of the suitability of the tool as an SBET-TCL (question 9). They believe that their level of knowledge about "Energy Efficiency" is considered high (question 1), because the theoretical concepts related to TCL were previously taught in theory classes. With respect to SBET-TCL experience, students agreed that theoretical concepts are strengthened and learning procedure is improved with the simulation platform (questions 2, 4 and 5). Otherwise, they do not think that theoretical concepts can be learned through theoretical study alone (question 3). A high level of acceptance by the students of the proposed tool is showed (question 6). Finally, students found the tool friendly and easy to use (questions 7 and 8), although they felt that the interface could be improved.

In addition, the main comments from students about the SBET-TCL are that it is really useful to learn about the behavior of TCLs and to realize that TCLs are a valuable tool to improve energy consumption in buildings. Even they also ask a way to delve deeper into the TCL models changing from the interface the value of the different model parameters RC.

6. Conclusions

A simulation-based educational tool specifically designed to teach TCLs is presented in this work. This tool overcomes the problems related to the expensive experimental training of engineers and students from other degrees or qualifications. The SBET-TCLs completes the theoretical training, showing the students the operation of TCLs and the necessity to control them to manage their consumption. The SBET-TCLs involves the TCLs most frequently found in a building as the electric space heating/cooling, refrigerators, freezers, and electric water heaters. The SBET-TCLs was evaluated by the students across several corresponding qualifications as a tool to complement the theoretical training. The results of the evaluation show that the students consider the SBET-TCLs as a very good tool to complete their training and felt that they had improved their qualifications in the TCL topic in comparison with previous academic years where the proposed tool was not used. Students were also interested in using the tool in other activities, such as their degree dissertation. With this aim in mind, they proposed some improvements, such as the inclusion of the possibility of modifying the RC parameters of the different models via the interface.

Moreover, given the good performance of the SBET-TCLs and the good results obtained in the academic experiment, there are proposals to use it in dissemination events such as 'the European Researchers Night'. In this event, researchers show their work directly to people. The SBET-TCLs will be used to make people aware of the importance of controlling their TCL behavior in order to manage their consumption, reduce global energy consumption, and slow down climate change.

Finally, in future work, the authors of the paper are constructing an experimental platform to test different strategies to control TCLs and to confirm TCL behavior under different conditions. The platform could also be used to characterize any kind of TCL other than those considered in this tool.

Author Contributions: Conceptualization, G.G.-R., R.S.-H. and J.M.A.; Methodology, G.G.-R., R.S.-H. and J.L.R.S.; Software, G.G.-R. and R.S.-H.; Validation, G.G.-R. and R.S.-H.; Formal analysis, G.G.-R., R.S.-H. and J.M.A.; Investigation, G.G.-R., R.S.-H. and J.M.A.; Resources, R.S.-H., J.M.A. and J.L.R.S.; Data curation, G.G.-R. and R.S.-H.; Writing – original draft, G.G.-R.; Writing – review & editing, R.S.-H. and J.M.A.; Visualization, G.G.-R. and R.S.-H.; Supervision, R.S.-H., J.M.A. and J.L.R.S.; Project administration, R.S.-H. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Ethical review and approval were not required for this study because it was non-interventional, no risks were involved, and participants were fully informed of the reasons for the research, how the information would be used, and their anonymity was guaranteed.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

TCLs parameters

Tables A1–A4 show the parameter values used in the simulations.

Table A1. Electric space heating/cooling parameters.

Parameter	Unit	Value
$R_{in,ia}$	KW^{-1}	0.007
$R_{ia,ex}$	KW^{-1}	0.007
$R_{ex,ea}$	KW^{-1}	0.1
$R_{ia,ea}$ [1]	KW^{-1}	0.01
C_{in}	JK^{-1}	500
C_{ex}	JK^{-1}	200
C_{ia}	JK^{-1}	80

[1] $R_{ia,ea}$ varies linearly from 0.01 if all doors and windows to the outside are closed to 0.001 if all are open. This means at the SBET-TCL interface (Figure 3) a percentage from 0% to 20%.

Table A2. Refrigerator parameters.

Parameter	Unit	Value
$R_{in,ex}$	KW^{-1}	2
$R_{in,ia}$ [1]	KW^{-1}	0.05
$R_{ex,ia}$	KW^{-1}	0.02
C_{in}	JK^{-1}	400
C_{ex}	JK^{-1}	100

[1] $R_{in,ia}$ is equal to 0.05 if the refrigerator door is closed. Otherwise, it is equal to zero.

Table A3. Freezer parameters.

Parameter	Unit	Value
$R_{in,ex}$	KW^{-1}	5
$R_{in,ia}$ [1]	KW^{-1}	0.05
$R_{ex,ia}$	KW^{-1}	0.05
C_{in}	JK^{-1}	200
C_{ex}	JK^{-1}	50

[1] $R_{in,ia}$ is equal to 0.05 if the freezer door is closed. Otherwise, it is equal to zero.

Table A4. Electric water heater parameters.

Parameter	Unit	Value
$R_{inw,ex}$	KW^{-1}	2
$R_{inw,suw}$ [1]	KW^{-1}	0.05
$R_{ex,suw}$	KW^{-1}	0.05
C_{inw}	JK^{-1}	150
C_{ex}	JK^{-1}	60

[1] $R_{inw,suw}$ is equal to 0.05 if the inlet valve of the electric water heater from the water supply to the building is closed. Otherwise, it is equal to zero.

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