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Towards More Sustainable Kitchens: Experimental Assessment of Energy Efficiency and Heat Losses in Turkish-Type Electric Tea Makers

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Abstract

Improving the energy efficiency of household appliances can reduce electricity consumption and support more sustainable kitchens. This study experimentally evaluates the energy performance and heat losses of Turkish-type electric tea makers. Three models with nominal powers of 1600–2000 W were tested using 74 valid observations. The average useful energy transferred to water was similar across the models (174–176 Wh), while electricity consumption was 228.57, 244.70, and 225.92 Wh for M1, M2, and M3, respectively. Their corresponding average energy efficiencies were 76.18%, 71.05%, and 77.73%. Model M2 had the shortest initial boiling time (200.16 s) but the highest electricity consumption. This shows that higher power does not necessarily improve cycle-level energy efficiency. The heat-loss analysis identified differences in surface and evaporation losses among the models. The findings provide experimental evidence to support energy-efficient appliance design and more sustainable household energy use.

Keywords: electric tea maker; energy efficiency; sustainable kitchens; heat loss; thermal imaging; household appliances

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1. Introduction

1.1. Background and Motivation

As the second most consumed beverage worldwide after water, tea has economic and cultural importance worldwide [1]. Türkiye ranks first worldwide in annual per capita tea consumption. A survey conducted in Adana and İzmir reported that 59.1% and 43.4% of participants, respectively, consumed 1–5 cups of tea daily, while some participants consumed more than 10 cups per day [2,3]. With approximately 245 million cups of tea consumed daily in Türkiye, this intensive consumption habit transforms tea from a mere beverage into an integral part of national culture and social life [4–6]. According to the Turkish Statistical Institute, annual per capita tea consumption in Türkiye averages 3.5 kg, placing it among the highest values worldwide [6,7].

Traditional Turkish tea brewing relies on a two-chamber system: a lower kettle for boiling water and an upper teapot for brewing [8]. Unlike single-chamber kettles, electric tea makers utilize two separate compartments to hold boiling water and tea infusion independently. This specialized design simplifies the brewing process, making these appliances ubiquitous in Turkish households [8]. Since electric kitchen appliances account

for a significant portion of residential energy consumption, they are critical for sustainability actions. Therefore, investigating the energy performance of tea preparation equipment is both meaningful and necessary.

Today, energy consumption and sustainability concerns are receiving increasing attention from policymakers, researchers, and consumers. According to data from the International Energy Agency (IEA), the residential sector accounts for approximately 27% of total global electricity consumption. Furthermore, small electrical household appliances in residential and commercial buildings constitute approximately 15% of this overall demand [9–11]. This proportion suggests that the potential energy savings achievable through efficiency improvements in these appliances are substantial.

The studies focusing on electric kettles reveal that energy demand can vary depending on design parameters. A comprehensive assessment of the European Union (EU) market estimated that if all new electric kettles met the lowest life-cycle cost level by 2023, annual energy consumption across the EU-27 would decrease from 9.8 TWh to 7.4 TWh, a 24.7% reduction [12]. This shows that improving the energy efficiency of small household appliances can support SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production). In evaluating the environmental impact of energy-using products like electric kettles, operational power usage is the primary contributor, accounting for 48% to 64% of the total environmental footprint [13]. Consequently, electric tea makers are categorized under electrical and electronic equipment (EEE) with significant improvement potential regarding energy efficiency, durability, and repairability [13]. According to industry data, annual sales of electric tea makers have reached approximately 2 million units. Given the 26.6 million households in Türkiye, these appliances are among the most widely used kitchen devices [14,15].

Widely cited metrics in energy efficiency evaluations include the primary energy factor, seasonal energy efficiency ratio (SEER), energy use intensity (EUI), and standby power. The IEC 62301 standard provides an internationally recognized methodology for measuring standby power in household electrical appliances [16]. Studies conducted under this framework emphasize that standby power losses in small appliances account for a non-negligible share of total residential energy use. Tea makers are considered high-priority appliances within this methodology due to their continuous heating cycles and prolonged standby modes [13].

In 2021, Türkiye ratified the Paris Agreement and updated its Nationally Determined Contribution (NDC), committing to reduce greenhouse gas emissions by up to 41% by 2030 compared to the business-as-usual scenario [17]. Furthermore, the Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM), introduced under the EU's carbon-neutral goal, place additional pressure on Türkiye—a major exporter to the EU—to track product-level carbon footprints and advance energy efficiency research [18,19]. National power demand is projected to increase by approximately 40% over the next 12 years compared to 2023 levels [3,20,21]. With increasing household electrification, quantifying the impact of electric tea makers on total energy demand is important. Even small efficiency improvements in frequently used appliances can reduce electricity consumption and potentially lower associated carbon emissions [21,22].

Tea makers constitute a significant segment of the kitchen electronics market, particularly in countries with high tea consumption, such as Türkiye, Iran, the United Kingdom, and China. In the literature, most studies investigating the energy efficiency of tea preparation have focused on electric kettles or stovetop teapots, providing essential thermodynamic data [8,23]. For instance, energy consumption and carbon footprint analyses of Turkish-type stovetop teapots by Zorlu et al. [24] provided valuable insights. Studies on single-chamber kettles highlight the decisive impact of user behavior; in the UK, three-

quarters of households overfill kettles, leading to an annual energy waste of up to 92 kWh per household [25].

1.2. Literature Review and Research Gap

Electric kettles generally operate in the 1500–3000 W power range. Studies evaluating their thermal efficiency primarily utilize the time required to reach boiling and heat loss rates as core performance indicators [26]. However, the electric tea makers widely used in Türkiye exhibit a more complex energy consumption pattern due to their dual-chamber structure, keep-warm functionality, and variable power stages. Systematic thermodynamic analyses of these specific dual-chamber appliances remain limited.

From the perspective of energy efficiency standards, regulations within the small home appliance category cover tea makers less comprehensively than products such as kettles and coffee machines. The EU Ecodesign Directive (2009/125/EC) does not define binding energy efficiency requirements specific to tea makers [27]. Similarly, the TS EN 60335-2-15 standard published by the Turkish Standards Institution (TSE) addresses safety and general performance criteria, but lacks a dedicated, comprehensive energy efficiency testing methodology for these devices [28]. Furthermore, standardization processes conducted by the U.S. Department of Energy (DOE) covering small electric kitchen appliances do not treat tea makers as a distinct product category [29]. However, few studies have examined how appliance design and usage patterns affect the energy efficiency of traditional tea preparation [30]. This limits the available evidence for improving these devices and reducing their electricity consumption [18,31]. This gap underscores the clear need for studies that address both user behavior and appliance design parameters within a holistic framework.

This study addresses this gap by comparing the energy performance of three Turkish-type electric tea makers under the same operating conditions. Electrical energy consumption, useful energy, and heat losses are evaluated using experimental measurements and thermal imaging. The results help identify factors affecting energy efficiency and provide a basis for improving appliance design. By focusing on electricity consumption during a complete brewing cycle, the study contributes to more sustainable kitchen appliances and responsible household energy use.

2. Materials and Methods

2.1. Experimental Setup and Measurement Devices

This study aims to compare different models of Turkish-type electric tea makers under identical consumer usage scenarios and to reveal their performance differences. For this purpose, three distinct models (M1, M2, and M3)—featuring a dual-chamber design with a lower kettle chamber and an upper teapot—were investigated. The nominal power, chamber capacity, and body material specifications of these appliances are summarized in Table 1. Various experimental data, including electrical energy consumption and temperature values, were recorded using GESI PM 1453 Shenzhen, China electrical power analyzer, a four-channel data logger, and thermocouples, while thermal distribution images were captured with a thermal camera, as detailed in Table 2.

2.2. Experimental Procedure

The experimental procedure was conducted as follows: water in the lower chamber was brought to the boiling point, and the hot water was then transferred to the upper teapot. The lower chamber was refilled with cold water and boiled a second time. Finally, a 20-min brewing and keep-warm phase was monitored, starting from the onset of the second boiling cycle [16].

Table 1. Main technical specifications of the Turkish-type electric tea makers used in the experiments.

Model	Nominal Power	Water Heater/ Lower Chamber Capacity	Teapot Capacity	Body Material
M1	1600 W	1.7 L	1.0 L	18/10 Cr-Ni stainless steel
M2	2000 W	1.7 L	1.2 L	18/10 Cr-Ni stainless steel
M3	1600 W	1.3 L	1.3 L	18/10 Cr-Ni stainless steel

Electrical energy was continuously recorded using GESI PM 1453, Shenzhen, China power analyzer. Thermocouples were placed in the internal liquid regions and on the external surfaces of both the kettle and teapot [31]. All temperature data measured by the thermal camera and thermocouples were recorded at 10-s intervals starting from t = 0. Regions of Interest (ROI) were defined on the thermal images for the kettle, teapot, and lid. Thermal images were acquired at a distance of approximately 0.30 m from the appliance surfaces. A surface emissivity of 0.95 was assumed for the infrared temperature measurements and corresponding radiative heat-loss calculations. This value was treated as a modeling assumption rather than an experimentally determined surface property.

Table 2. Measuring instruments and technical specifications used in the experiments.

Measuring Instrument	Brand and Model	Measured Quantity	Key Technical Specifications
Thermal Camera	Bosch GTC 12V-450-13	External surface temperature and temperature distribution	256 × 192 pixels (49,152 points); −20 to 450 °C; accuracy ±2 °C; resolution 0.1 °C; 9 Hz; NETD ≤ 50 mK
Four-Channel Data Logger and Thermocouples	CEM DT-3891G	Water temperature and point surface temperatures	4 channels; K/J type; K: −200 to 1372 °C, J: −210 to 1100 °C; accuracy ±0.15% reading + 1 °C; resolution 0.1 °C; 18,000 readings per channel
Power Analyzer	Specified per device technical documentation	Voltage, current, frequency, power factor, active and reactive energy	Voltage/Current ±0.5%; Frequency ±0.1%; Power factor ±0.2%; Active energy ±1% or ±0.5%; Reactive energy ±2% or ±1%

Following data screening, 74 observations were retained for statistical analysis, comprising 24 runs for M1 and 25 runs each for M2 and M3.

2.3. Calculations

The total energy input supplied to the appliance is defined as the electrical energy measured by the power analyzer, as given in Equation (1):

$$E_I = E_{el} \quad (1)$$

The useful energy transferred to the water is calculated using Equation (2) [32]:

$$E_W = \frac{m_W \cdot c_{p,W} \cdot (T_B - T_i)}{3600} \quad (2)$$

where m is the mass of water (kg), c_p is the specific heat capacity (J/kg · K), T_i (°C) is the initial temperature, T_β (°C) is the onset boiling temperature. For this study, useful thermal energy was defined as the sensible heat required to raise a total of 2 L of water to the boiling temperature. The experimental procedure consisted of two consecutive heating stages. First, 1 L of water was heated to boiling and transferred to the upper teapot. Subsequently, another 1 L of water was added to the lower chamber and heated to boiling.

The 20-min brewing period was measured from the beginning of the second heating stage and therefore included approximately 3 min required for the second boiling process. The total electrical energy input, however, was measured over the entire experimental cycle, lasting approximately 23 min, including both heating stages and the remaining brewing and keep-warm period. Accordingly, the calculated efficiency represents a cycle-level performance indicator based on the sensible heating of 2 L of water, rather than the total thermal energy delivered during the keep-warm period. The thermal efficiency is calculated as the ratio of useful energy to the electrical energy input, as expressed in Equation (3) [33]:

$$\eta = \frac{E_W}{E_E} \times 100 \tag{3}$$

The average energy efficiencies reported in this study represent the arithmetic mean of the efficiency values calculated individually for each experiment. Therefore, slight variations may exist compared to the ratio of average useful energy to average electrical energy consumption.

The total energy loss E_L (Wh), defined as the difference between the electrical energy input and useful energy, is calculated using Equation (4):

$$E_L = E_E - E_W \tag{4}$$

Natural convection heat loss from the external surfaces of the kettle, teapot, and lid is calculated for each 10-s time step using Equation (5) [32]:

$$Q_{NC} = \sum_i \frac{h_{i.}.A_s.(T_{s,i} - T_\infty).\Delta t}{3600} \tag{5}$$

where h is the natural convection coefficient, A_s is the surface area (m^2), $T_{s,i}$ is the surface temperature (°C), T_∞ is the ambient temperature (°C), and Δt is the time interval (s). Radiation loss was calculated using the Stefan–Boltzmann relationship presented in Equation (6) [32]:

$$Q_R = \sum_i \frac{\varepsilon \sigma A_s \left(T_{s,i}^4 - T_\infty^4\right) \Delta t}{3600} \tag{6}$$

where ε is the surface emissivity and σ is the Stefan–Boltzmann constant ($W/m^2 \cdot K^4$). Temperatures in the equation are expressed in Kelvin. The total energy loss from the external surfaces is given by Equation (7):

$$Q_{TS} = Q_{NC} + Q_R \tag{7}$$

Evaporation loss is calculated from the mass difference before and after the experiment and the latent heat of vaporization, as shown in Equation (8):

$$Q_V = \frac{m_V \cdot h_{fg}}{3600} \tag{8}$$

where m_V is the evaporated water mass (kg) and h_{fg} is the latent heat of vaporization (J/kg). A single dedicated evaporation experiment was performed for each model, and the measured mass loss was used as a representative value in the heat-loss calculations. The mass measurements were performed using an electronic weighing scale with a maximum capacity of 40 kg, a minimum load of 200 g, and a scale interval of 2 g (d = e = 2 g). Evaporative mass loss was determined from the difference between the initial and final masses. The 2 g scale interval was considered a limitation of the mass measurements.

The total modelled loss energy is calculated using Equation (9):

$$Q_{TL} = Q_{TS} + Q_V \quad (9)$$

Thermal camera temperature readings were utilized to calculate heat losses from external surface areas, whereas thermocouples were used to monitor internal temperatures and validate surface temperature measurements. The calculated losses were compared with the energy loss determined via Equation (4).

The energy-balance residual E_{res}, defined in Equation (10), represents the difference between the measured electrical energy input and the sum of the calculated useful energy and modeled heat losses:

$$E_{res} = Q_E - Q_{TLM} - Q_W \quad (10)$$

This term accounts for unmodeled physical losses as well as measurement and modeling uncertainties.

2.4. Statistical Analysis

Statistical analyses were conducted to evaluate differences among the three tea-maker models. Following the exclusion of one duplicate record, 74 experimental observations were included (M1: n = 24; M2: n = 25; M3: n = 25).

Data normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. One-way ANOVA followed by Tukey's HSD test was applied to electrical energy consumption, useful energy, and energy efficiency. Since the assumptions were not fully satisfied for initial boiling time, the Kruskal–Wallis test followed by Dunn's post-hoc test with Holm adjustment was used.

Statistical significance was evaluated at $p < 0.05$. Evaporative heat losses were excluded from inferential statistical analyses because only one dedicated evaporation measurement was performed for each model. Descriptive results are presented as mean ± standard deviation (SD), where SD represents the variability among repeated experimental observations.

For the validation analysis, infrared temperatures were extracted from local regions of interest (ROIs) selected near the estimated thermocouple contact locations on the brewer and boiler surfaces in the thermal-image matrices of Experiment 4. Local neighborhood averaging was applied to reduce pixel-level variations. Local averaging was performed over 3 × 3 pixels for the brewer and 9 × 9 pixels for the boiler, using regions selected near the estimated thermocouple contact locations. The resulting infrared temperatures were paired with the corresponding thermocouple measurements at 10 s intervals between 10 and 400 s, excluding the missing thermal frame at 370 s. Linear regression and Bland–Altman analyses were performed to assess the relationship and agreement between the two measurement methods. The corresponding results are presented in Supplementary Figure S1.

2.5. Use of Generative Artificial Intelligence

For the validation analysis, ChatGPT (GPT-5.6, OpenAI; San Francisco, CA, USA, accessed 9 July 2026) was used as a computational assistant. ChatGPT (OpenAI) was used as a computational assistant for statistical analysis and thermal-camera validation. For the statistical analysis, ChatGPT assisted with data processing, normality and variance homogeneity tests, ANOVA, Tukey's HSD, Kruskal–Wallis, and Dunn's post-hoc comparisons. The statistical results were reviewed and verified by the authors before inclusion in the manuscript. For the thermal-camera validation, ChatGPT was used to align infrared and thermocouple temperature data, calculate MAE, RMSE, and Bias, and prepare the validation plots. The invalid thermal frame at 370 s was excluded from the analysis.

No experimental data were generated or altered by the AI tool. The experimental design, measurements, interpretation of the results, and scientific conclusions were the responsibility of the authors.

3. Results and Discussion

3.1. Energy Performance and Heat-Loss Distribution

The useful energy values calculated from 74 valid experimental observations (M1: n = 24; M2: n = 25; M3: n = 25) were found to be very similar across the three tea-maker models. The average useful energy transferred to the water was calculated as 173.97 ± 2.12, 173.77 ± 2.77, and 175.51 ± 2.16 Wh for models M1, M2, and M3, respectively. The difference between the highest and lowest average values was only 1.75 Wh, representing a variation of approximately 1%. This similarity indicates that all three models were tested under comparable useful thermal loads, demonstrating that performance discrepancies stem from electrical input and heat loss mechanisms rather than the energy successfully transferred to the water.

Average electrical energy consumption was measured as 228.57 ± 6.77, 244.70 ± 7.41, and 225.92 ± 5.76 Wh, for M1, M2, and M3, respectively. Accordingly, the average energy efficiencies calculated on a per-experiment basis—as shown in Figure 1 & Table 3—were 76.18% ± 2.31, 71.05% ± 1.61, and 77.73% ± 1.72, respectively. Model M3 exhibited the lowest average electricity consumption and the highest average energy efficiency among the investigated models. Although the electricity consumption of M3 was only 1.15% lower than that of M1, its energy efficiency was 1.55 percentage points higher. In contrast, M2 consumed 7.67% more electrical energy than M3 and demonstrated an average efficiency that was 6.67 percentage points lower. These results indicate that nominal electrical power alone does not dictate cycle energy consumption or overall energy efficiency.

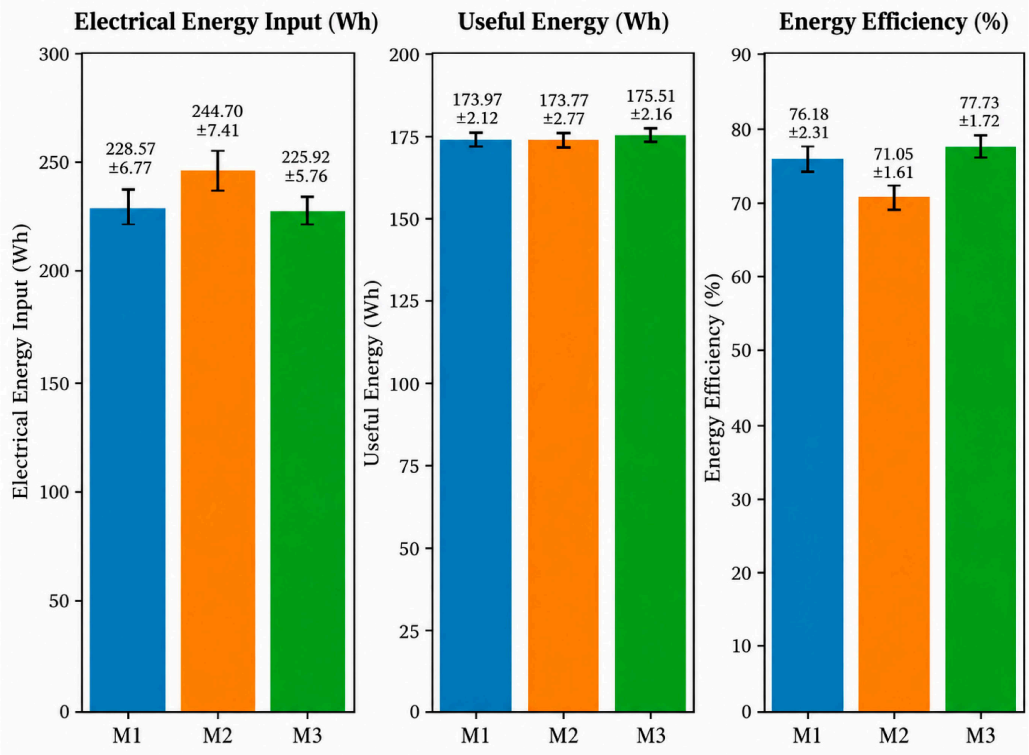


Figure 1. Electrical energy consumption, useful energy transferred to water, and average energy efficiency of models M1, M2, and M3. Error bars represent ±1 standard deviation (M1: n = 24; M2: n = 25; M3: n = 25).

Table 3. Descriptive statistics of the energy performance of the three electric tea-maker models.

		Energy Input (Wh)			Useful Energy (Wh)			Energy Efficiency (%)		
Model	**n**	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**
M1	24	228.57 ± 6.77	216.00	242.60	173.97 ± 2.12	170.22	177.19	76.18 ± 2.31	71.73	80.54
M2	25	244.70 ± 7.41	230.00	257.00	173.77 ± 2.77	166.74	177.65	71.05 ± 1.61	68.74	75.02
M3	25	225.92 ± 5.76	214.00	235.00	175.51 ± 2.16	171.84	179.04	77.73 ± 1.72	75.20	81.12

The descriptive statistics presented in Table 3 indicate differences in the energy performance of the three tea-maker models. As shown in Table 4, these differences were statistically significant for electrical energy consumption, useful energy, energy efficiency, and initial boiling time ($p < 0.05$). Model M2 exhibited the highest electrical energy consumption (244.70 Wh) and the lowest energy efficiency (71.05%), whereas M3 achieved the highest efficiency (77.73%). Post-hoc comparisons confirmed differences in efficiency among all three models. Although M3 consumed slightly less electricity than M1 (225.92 vs. 228.57 Wh), this difference was not statistically significant. Model M2 also exhibited a shorter initial boiling time than the other two models. These findings suggest that faster boiling does not necessarily correspond to lower overall energy consumption or higher cycle-level efficiency.

Table 4. Statistical comparison of the energy performance indicators among the three tea-maker models.

Performance Indicator	**Statistical Test**	**Test Statistic**	***p*-Value**	**Effect Size (η^2)**
Energy efficiency (%)	One-way ANOVA	F(2,71) = 84.31	<0.001	0.704
Electrical energy input (Wh)	One-way ANOVA	F(2,71) = 57.63	<0.001	0.619
Useful energy (Wh)	One-way ANOVA	F(2,71) = 4.02	0.022	0.102
Initial boiling time (s)	Kruskal–Wallis	H(2) = 45.47	<0.001	0.612 *

M1: n = 24; M2: n = 25; M3: n = 25. Significance threshold: $p < 0.05$. * The Kruskal–Wallis effect-size value is η^2(H), not the conventional ANOVA η^2.

The difference between the measured electrical energy input and the calculated useful energy transferred to the water was 54.60, 70.93, and 50.41 Wh for M1, M2, and M3, respectively. In comparison, the total modeled heat losses, comprising external surface losses and evaporation losses, were 71.05, 58.86, and 50.90 Wh, respectively. Accordingly, the energy-balance residuals were calculated as −16.45 Wh for M1, +12.07 Wh for M2, and −0.49 Wh for M3, as illustrated in Figure 2. These residuals yield −7.2%, +4.9% and −0.2% of the energy input for M1, M2 and M3, respectively.

The negative residual for M1 indicates that the modeled heat losses exceeded the difference between electrical input and useful energy, suggesting possible overestimation of one or more loss components. Conversely, the positive residual for M2 indicates that the measured energy difference exceeded the modeled losses, potentially reflecting unaccounted energy transfers, thermal storage, or modeling uncertainties. The near-zero residual for M3 indicates close numerical agreement between the measured energy difference and the modeled heat losses. However, this result should not be interpreted as proof of superior model accuracy, since opposing measurement and modeling errors may partially cancel each other. Overall, the residuals represent energy-balance discrepancies rather than independently verified heat-loss mechanisms.

A detailed distribution of the heat loss components is presented in Figure 3. Natural convection losses were calculated as 18.97, 16.85 and 16.31 Wh for M1, M2, and M3, respectively, while radiation losses were 20.73, 20.07, and 18.92 Wh. Consequently, the

total external surface losses varied within a narrow range across models (39.70, 36.92, and 35.22 Wh, respectively). However, a distinct variation emerged in terms of evaporation losses: 31.35 Wh for M1, 21.94 Wh for M2, and 15.67 Wh for M3. The evaporation loss of M1 was approximately twice that of M3.

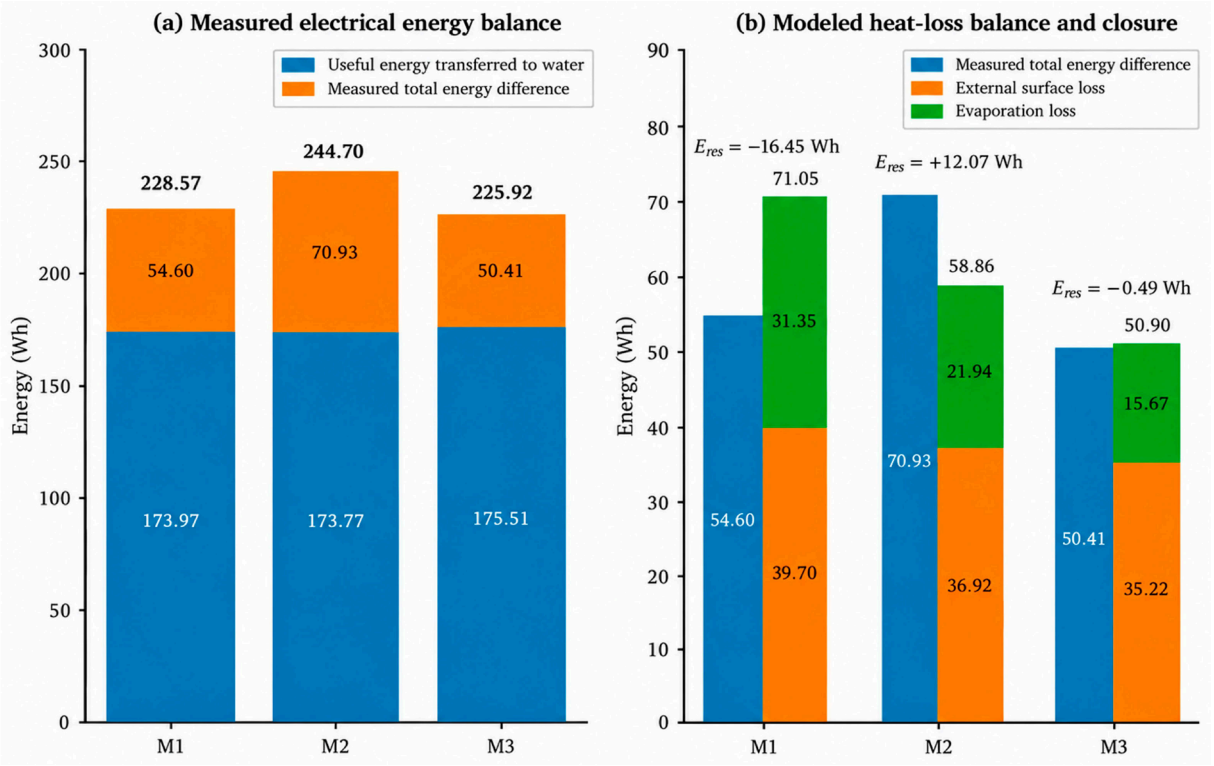


Figure 2. Comparison of the measured electrical energy balance, modeled heat losses, and energy-balance residual for models M1, M2, and M3.

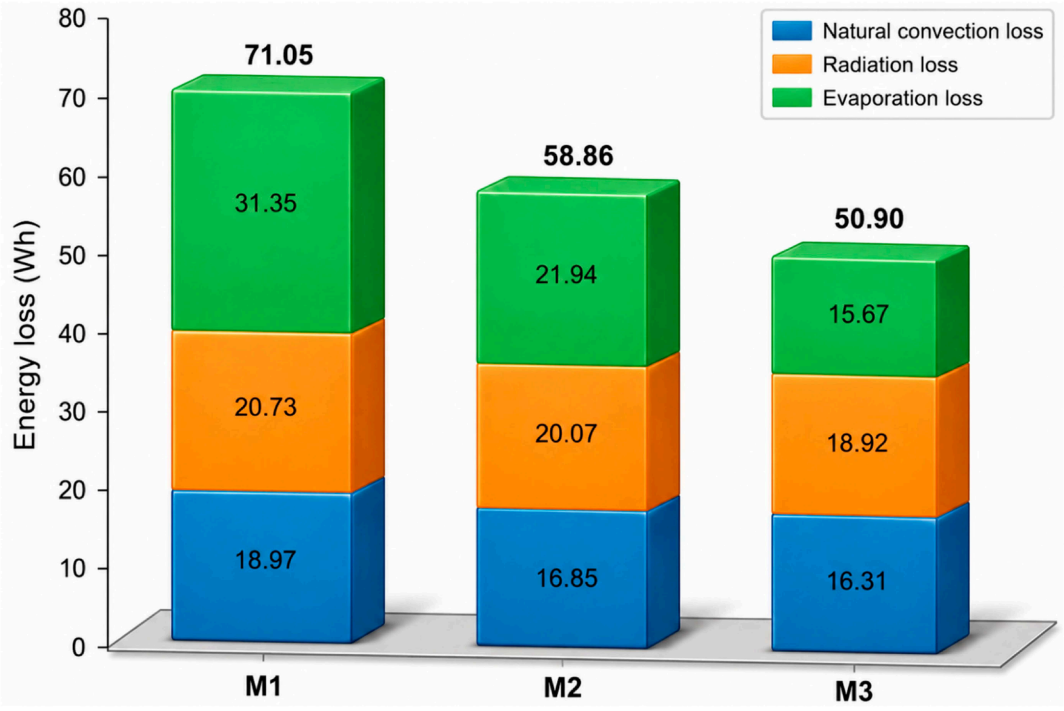


Figure 3. Distribution of natural convection, radiation, and evaporation losses for models M1, M2, and M3.

M3 had the highest average energy efficiency and the lowest calculated heat losses. Its representative evaporation loss was also lower than those of M1 and M2. However, since evaporation was measured only once for each model, its contribution to the observed efficiency differences cannot be established conclusively. Although the difference in external surface losses between M1 and M3 was small, the disparity in evaporation loss critically affected total modeled losses and overall efficiency. Furthermore, M2 exhibited the highest electrical energy consumption; its calculated surface and evaporation losses were lower than those of M1. This indicates that variations in total energy consumption cannot be explained solely by observed external surface mechanisms.

As shown in Figure 3, while surface losses were close among the three models (35.22–39.70 Wh), the primary differentiation emerged in evaporation loss: 31.35 Wh for M1, 21.94 Wh for M2, and 15.67 Wh for M3. Consequently, the performance superiority of M3 is associated with its lower electrical consumption alongside lower evaporation and total calculated losses.

3.2. Brewing Stages and Surface-Temperature Validation

In the validation experiment conducted for Model M2, thermal images and temperatures recorded from four thermocouples were collected simultaneously at 10-s intervals. These measurements facilitated the identification of three main operating stages via temperature–time curves: initial boiling, hot-water transfer to the teapot followed by refilling the kettle with cold water, and the keep-warm phase.

As illustrated in Figure 4, during the initial boiling stage, *T2* (representing the water temperature inside the kettle) reached 99.8 °C at approximately 200 s, while the kettle external surface temperature *T4* remained at around 62.5 °C. Upon transferring the hot water to the teapot at approximately 210 s, *T2* dropped from 99.8 °C to 24.0 °C; conversely, *T3* rose from 32.7 °C to 91.9 °C and *T1* increased from 32.9 °C to 76.6 °C.

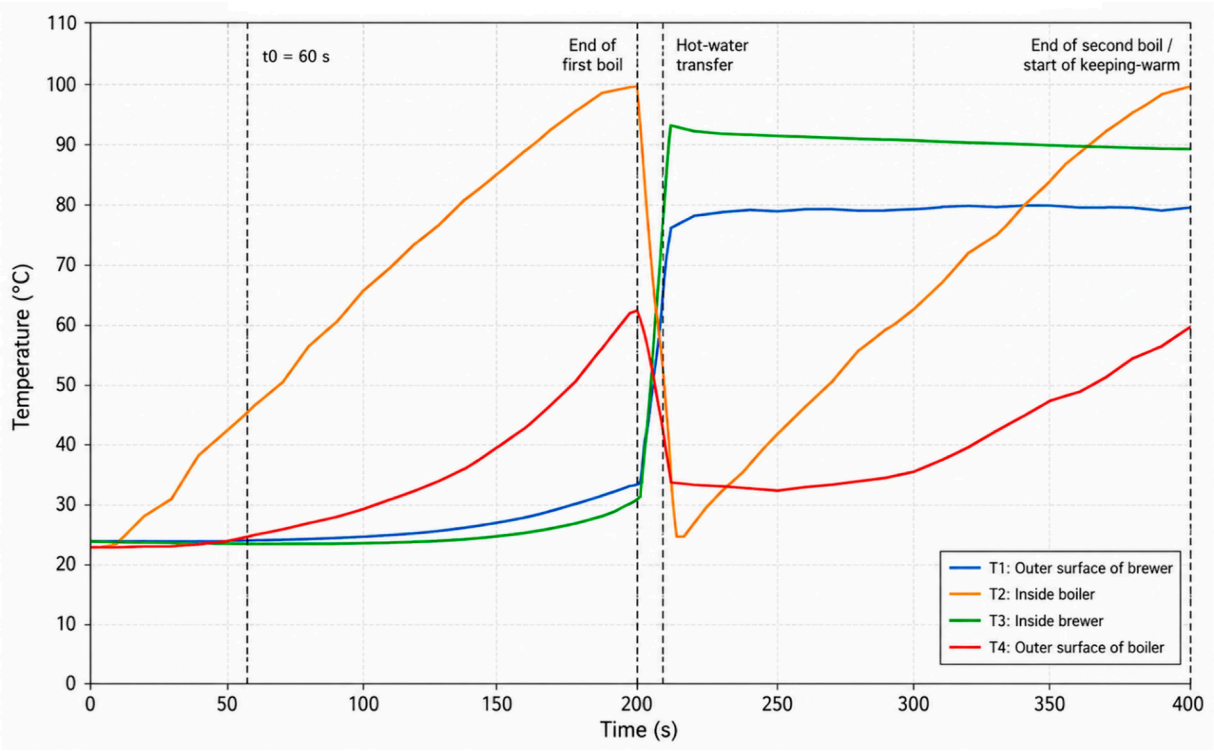


Figure 4. Time-dependent thermocouple temperatures measured during Experiment 4 of model M2 and identification of the principal brewing stages.

At the end of the second boiling stage, at approximately 400 s, *T2* reached 99.7 °C again, while the internal teapot temperature was maintained within the range of 89–92 °C. This behavior indicates that following the hot water transfer, the teapot maintained its elevated temperature while the water in the lower chamber was re-boiled [10–12]. It should be noted that Figure 4 presents the temperature–time profiles obtained from Experiment 4 of Model M2 as a representative example to illustrate the thermal behavior of the tea maker during different operating stages. In contrast, the comparative energy performance results reported in this study are based on the mean values obtained from the repeated experiments.

Although electrical energy was continuously supplied during the first phase of the experiment, the temperature rise on the external surfaces remained limited (Figure 5). This lag was attributed to the thermal inertia of the heating element, base region, and internal components. It was incorporated into the external surface loss model as an initial delay of t_0 = 60 s. This delay denotes the onset of measurable heat loss from external surfaces rather than a delay in electrical power input. Thermal images confirmed that heat was redistributed between the kettle and teapot surfaces after the hot-water transfer, and external surface temperatures consistently lagged behind internal liquid temperatures.

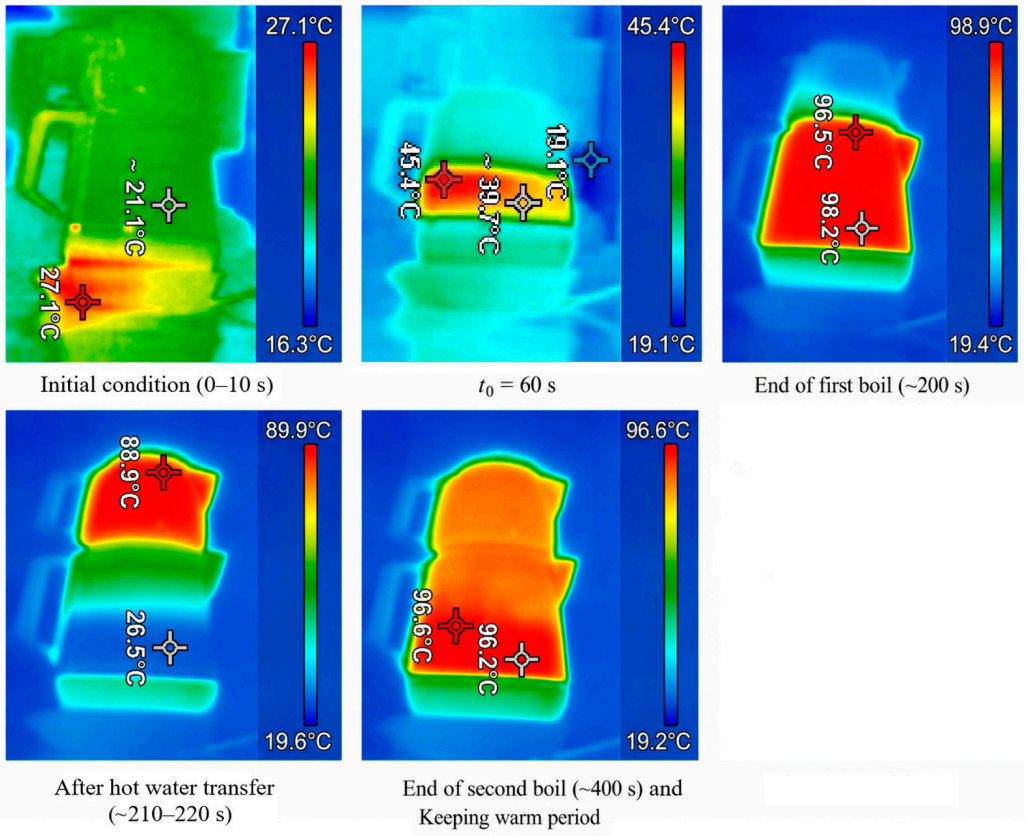


Figure 5. Selected thermal frames showing the evolution of the external surface-temperature distribution during the brewing cycle of model M2.

The infrared ROI temperatures obtained from Experiment 4 were compared with the corresponding thermocouple measurements (T1 and T4) to evaluate their agreement (Figure 5). The analysis included 39 paired observations for each surface over the 10–400 s interval, excluding the missing thermal frame at 370 s. For the brewer outer surface, the MAE, RMSE, and Bias were 1.72 °C, 2.23 °C, and +0.15 °C, respectively. Linear regression yielded R^2 = 0.995, while Bland–Altman analysis indicated 95% limits of agreement of −4.28 to +4.58 °C. For the boiler outer surface, the corresponding MAE, RMSE, and Bias

values were 3.34 °C, 4.03 °C, and +0.43 °C, respectively, with R^2 = 0.871 and 95% limits of agreement of −7.52 to +8.38 °C (Figure 6). The regression and Bland–Altman plots are presented in Supplementary Figure S1. These findings indicate closer agreement between the two measurement methods for the brewer surface than for the boiler surface. The wider limits of agreement observed for the boiler may be associated with surface curvature, spatial temperature gradients, differences in measurement locations, and rapid thermal transitions.

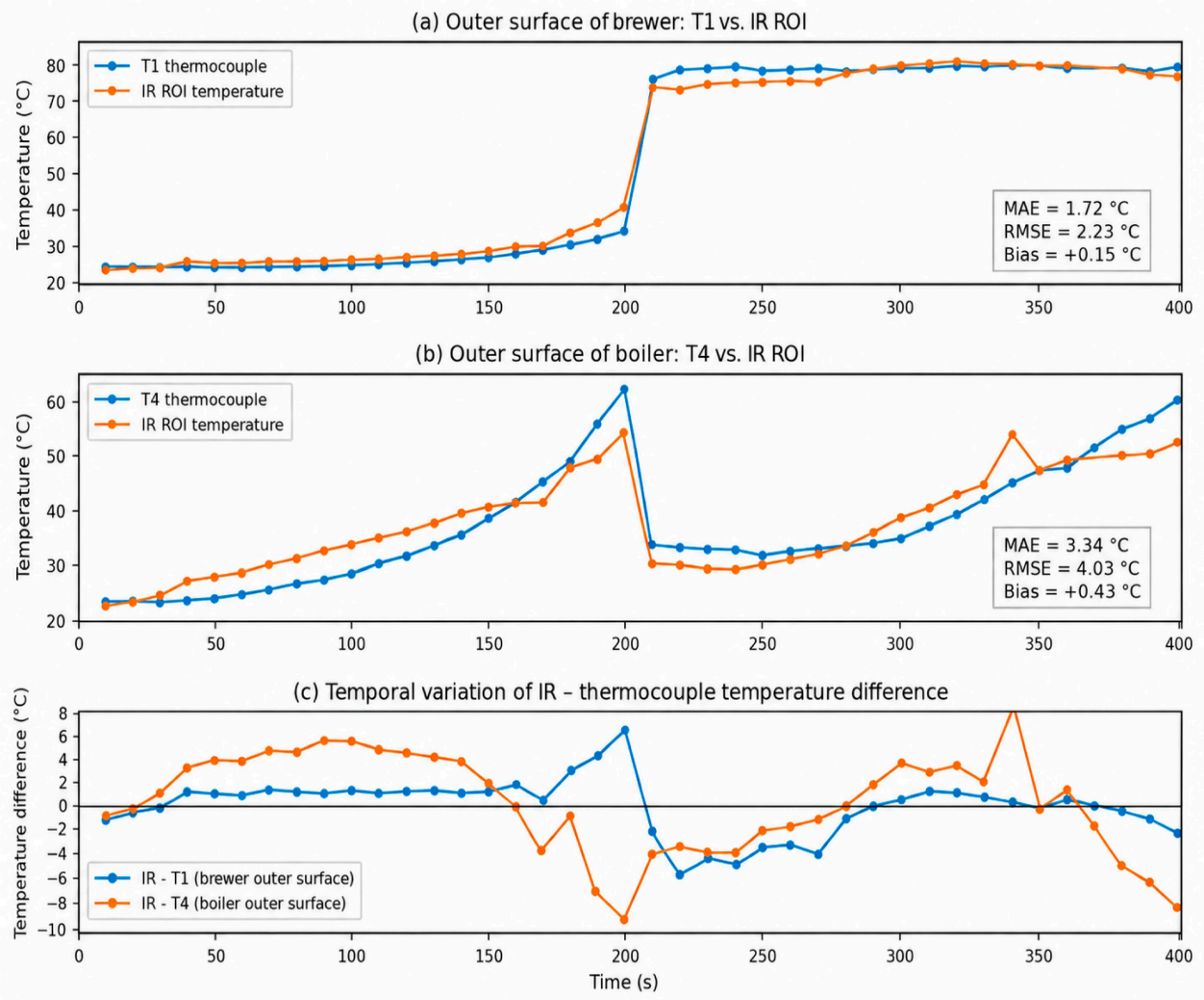


Figure 6. Validation of thermal camera ROI temperatures against thermocouple measurements for the outer surfaces of the brewer and boiler.

3.3. Sensitivity Analysis of the Heat-Loss Model

The sensitivity of the heat loss model to its underlying assumptions was investigated by varying each parameter individually while holding the others constant. The parameter variations included ±3 °C for surface temperatures, ±20% for natural convection coefficients, ±5% for surface areas, ±10% for evaporative losses, and t_0 = 60 ±10 s for the initial delay time. An additional scenario evaluating a reduction in emissivity from ε = 0.95 to 0.85 was also included.

Among the comparison parameters, the highest relative sensitivity was observed for the natural convection coefficient, as shown in Figure 7. Varying the coefficient by ±20% changed the total calculated heat loss by approximately ±3.79 Wh, ±3.37 Wh, and ±3.26 Wh for M1, M2, and M3, respectively. These changes correspond to ±5.34%, ±5.72%, and ±6.41% of the respective total calculated heat losses. A ±3 °C variation in surface

temperature resulted in changes of −2.62/+2.67 Wh for M1, −2.15/+2.19 Wh for M2, and −2.22/+2.26 Wh for M3. Accordingly, the relative effect of temperature sensitivity remained within approximately 3.7–4.4%.

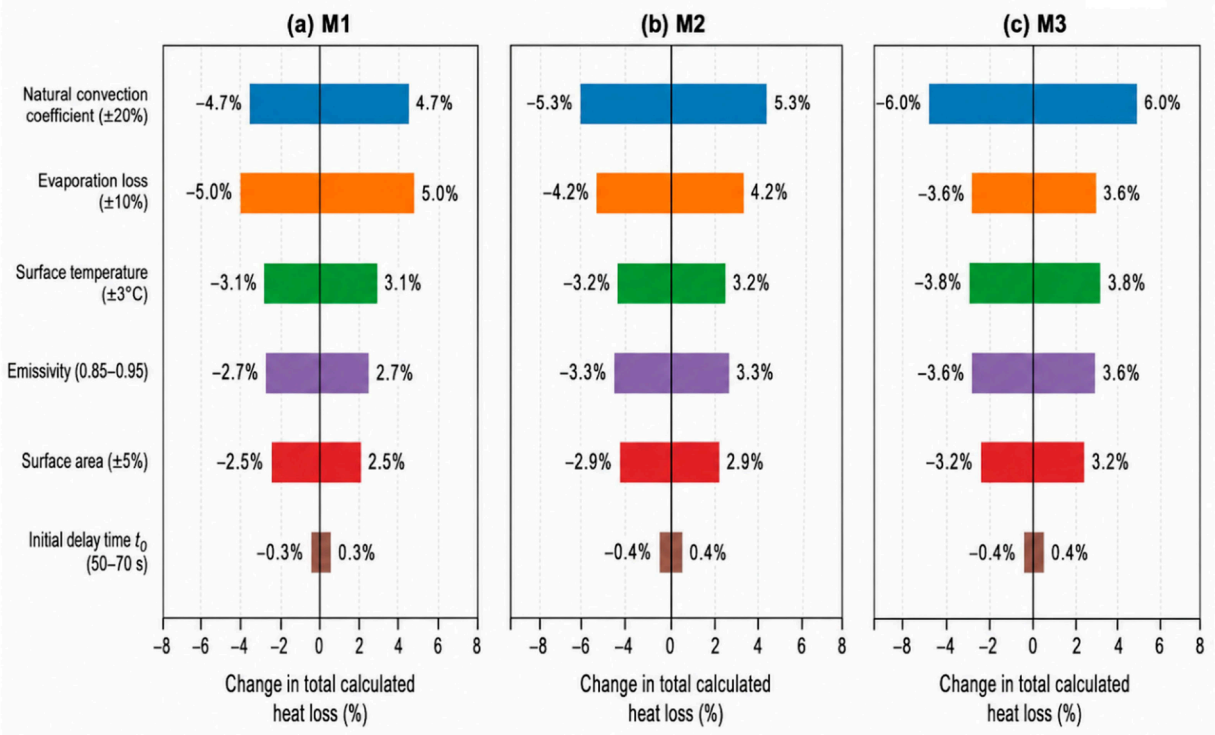


Figure 7. Sensitivity of total calculated heat loss to key uncertainty parameters for models M1, M2, and M3.

A ±10% variation in evaporative heat loss affected the total heat loss by ±3.13, ±2.19, and ±1.57 Wh for M1, M2, and M3, respectively. The higher sensitivity to evaporation in M1 is attributed to the larger measured evaporative heat loss in this model compared with the other models. Reducing the emissivity from 0.95 to 0.85 decreased the total calculated heat loss by approximately 2.01–2.29 Wh, corresponding to 3.2–3.9%, across the models. The effect of a ±5% variation in surface area remained at approximately ±1.76–1.98 Wh.

Varying the initial delay time within the range of 50–70 s affected the total calculated heat loss by only approximately 0.16–0.21 Wh, corresponding to about 0.3%. Thus, the effect of the t_0 assumption on the results was found to be limited compared with the other model parameters. Across all investigated single-parameter variations, the ranking of the total calculated heat losses remained unchanged as M1 > M2 > M3. However, the sensitivity analysis evaluates only the supporting heat loss model and does not directly assess the energy efficiency calculation based on measured electrical consumption and useful energy.

3.4. Discussion and Practical Implications

The experimental results confirm that the average useful energy transferred to the water remained tightly within the 174–176 Wh range across all models, ensuring that the devices were evaluated under similar calculated useful-energy values. However, electricity consumption and average energy efficiency varied depending on the design. Although M1 and M3 share the same nominal power (1600 W), their average electricity consumptions were similar (228.57 and 225.92 Wh), but their average energy efficiencies were 76.18% and 77.73%, respectively. M2, despite possessing a higher nominal power of 2000 W, exhibited the highest average electricity consumption (244.70 Wh) and the lowest average energy efficiency (71.05%).

The difference in electricity consumption also has implications for sustainable household energy use. Under the same experimental conditions, M3 consumed 18.78 Wh less electricity per cycle than M2, corresponding to a reduction of approximately 7.7%. For a household using the appliance twice a day, this difference would amount to approximately 13.7 kWh per year, assuming similar operating conditions throughout the year. Although the saving per cycle is small, the cumulative effect may become significant when considering the widespread use of electric tea makers. This example illustrates how appliance design can contribute to reducing household electricity demand for a sustainable future.

The higher nominal power of M2 provided a distinct advantage in boiling time, reaching the first boil at 200.16 s (approximately 54 s earlier than M1 and 44 s earlier than M3). According to manufacturer specifications, this higher nominal power and a slightly higher keep-warm temperature are intended to offer users shorter preparation times and hotter serving temperatures. The observed temperature–time behavior aligns with this comfort-oriented design approach.

However, the shorter boiling time did not translate into a reduction in total energy consumption per cycle [34]. Although M2's calculated external surface and evaporative losses were lower than those of M1, its overall electricity consumption was higher. The positive residual energy difference (+12.07 Wh) for M2 may indicate that its energy consumption involves mechanisms beyond natural convection, radiation, and evaporation. Unmeasured transient effects, such as base–heater losses and control system cycling, likely contribute to this difference. Thus, the lower energy efficiency of M2 cannot be attributed to a single design component.

Among the modeled losses, external surface losses varied within a relatively narrow range of 35.22–39.70 Wh across the three models, whereas a more pronounced difference was observed in evaporative losses. The evaporative loss of M1, at 31.35 Wh, was approximately twice that of M3, which was 15.67 Wh. Therefore, a substantial portion of the difference in total calculated heat loss between M1 and M3 can be associated with their evaporation behavior. The lowest total modeled heat loss observed for M3 resulted from the combined effect of its lower external surface loss and lower evaporative loss.

The results indicate that design improvements should not focus solely on the nominal heater power. Key areas for improvement include optimizing steam outlet paths and lid geometry, limiting unnecessary evaporation, reducing the area and temperature of hot surfaces, improving thermal contact between the heater and water, and insulating the base region. Managing the keep-warm function gradually according to the duration of use or consumer demand, rather than maintaining a constant high temperature, may also reduce energy consumption while preserving user comfort [20].

The primary limitation of this study is that heat losses from the base, energy stored in the body components, and the energy consumed by the control systems were not measured directly. Future studies should employ heat flux sensors in the base region and test devices under varying keep-warm durations and water volumes to further isolate design-related performance factors.

Evaporative heat losses were estimated using a single dedicated measurement for each model. These measurements were treated as representative values in the energy-balance calculations. Therefore, differences in evaporation losses should be interpreted descriptively and cannot be considered statistically significant.

4. Conclusions

In this study, the energy performance of three distinct Turkish-type electric tea makers was evaluated based on 74 valid experimental observations (M1: n = 24; M2: n = 25; M3: n = 25). While the useful energy transferred to the water was virtually identical across

the models (174–176 Wh), disparities were observed in electricity consumption and energy efficiency. The 2000 W model (M2) provided the fastest boiling time but yielded the highest electricity consumption and the lowest average energy efficiency (71.05%).

Calculated heat losses (natural convection, radiation, and evaporation) were 71.05, 58.86, and 50.90 Wh for M1, M2, and M3, respectively. While external surface losses were relatively consistent across the models, evaporation losses varied. Model M1 exhibited an evaporation loss of 31.35 Wh, compared with the representative value of 15.67 Wh obtained for M3. The residual energy balance for M3 was close to zero (−0.49 Wh), whereas M1 and M2 exhibited residuals of −16.45 and +12.07 Wh, respectively. These residuals underscore the necessity of directly measuring base–heater losses and control-system behaviors in future investigations.

The thermocouple and thermal camera data clearly distinguished the first boiling, hot-water transfer, second boiling, and keep-warm stages. The thermal-camera validation yielded MAE values of 1.72 °C for the brewer and 3.34 °C for the boiler surfaces. The relatively low mean Bias values indicated limited average signed deviations between the two measurement methods. Regression and Bland–Altman analyses revealed closer agreement for the brewer surface than for the boiler surface, where wider limits of agreement were observed. The sensitivity analysis showed that the calculated total heat loss was most affected by the natural convection coefficient, surface temperature, and evaporative loss, whereas the effect of the initial delay remained limited to approximately 0.3%. The ranking of the total calculated heat losses remained unchanged over the parameter ranges investigated.

The results demonstrate that, in Turkish-type electric tea makers, a higher nominal power can reduce the time to boiling but does not necessarily result in higher energy efficiency. To improve energy performance, limiting evaporation, reducing external surface and base losses, improving heat transfer between the heater and water, and optimizing keep-warm control according to user requirements should be considered as priority design strategies. To generalize these findings to a broader range of products, standardized comparative experiments under different device designs, water volumes, serving temperatures, and extended keep-warm conditions are required.

These findings can support the development of more energy-efficient tea makers and contribute to sustainable kitchens. Future studies should also examine long-term electricity consumption, user behavior, and environmental impacts to assess the broader sustainability benefits of improved appliance designs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182110714/s1, Figure S1: Statistical comparison of infrared thermal-camera ROI temperatures and thermocouple measurements for the outer sur-faces of the (**a**,**c**) upper brewer and (**b**,**d**) lower boiler during Experiment 4. Panels (**a**,**b**) show linear regression analyses, including the 1:1 reference line, fitted regression line, and coefficient of determination (R^2). Panels (**c**,**d**) present Bland–Altman analyses, showing the mean measurement difference (Bias) and 95% limits of agreement (mean difference ± 1.96 SD). The analysis includes 39 paired observations for each surface, recorded at 10 s intervals between 10 and 400 s, excluding the missing measurement at 370 s.

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Conflicts of Interest: Authors Batuhan Göçen, Berke Güler and Mücahit Baruğ were employed by the company R&D Center, Korkmaz Mutfak Eşyaları San. ve Tic. A.Ş., Istanbul, Turkey (Türkiye). The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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