

How much Energy is Embodied in your Central Heating Boiler?

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Abstract. Life Cycle Analysis (LCA) is an important tool in current research to quantitatively assess energy consumption and environmental impact of a building. In the context of LCA, the Embodied Energy (EE) related to the building and the corresponding Embodied CO₂ emissions are valuable data. In such a case, these data concern the constitutive materials of the building and any subsystem, component or equipment in it. Usually, after calculating the mass of these materials, embodied energy values are estimated multiplying them by the corresponding EE coefficients concerning the production of these materials (EE_{MP}). However, apart from transportation energy costs, another part of EE is that consumed for the manufacturing of any item as a finished product. The present work focuses on the manufacturing EE (EE_{MFG}) of central heating boilers in Hellenic dwellings. Six typical boilers of different types are studied. Each of them is analyzed to its constitutive materials and its EE_{MP} is estimated. For four of them, the boiler house where it was constructed in Greece was visited and data were collected. Based on them the corresponding boiler EE_{MFG} values are estimated. The results concerning the EE for material production and manufacturing, as well as the results concerning the corresponding ECO₂ values are discussed and assessed. Benchmark values correlating EE and ECO₂ with the mass or the heat rate of the boiler are extracted.

1. Introduction

Buildings are responsible for about 40% of the total energy consumption and about one third of total CO₂ emissions in Europe [1]. Current practice and legislation focuses on the Near Zero Energy Building (NZEB). Furthermore, current research points to the concept of Life Cycle Zero Energy Building (LCZEB) [2]. In the context of performing Life Cycle Analysis of a building, its Life Cycle Energy (LCE) has to be estimated. LCE comprises of two major parts; its Embodied Energy (EE) and its Operational Energy (OE) [3]. Operational energy refers to the amount of energy consumed by the building to fulfill the requirements concerning water supply, heating, cooling, ventilation, lighting, hot water, sanitation and operation of various appliances and equipment. On the other hand, Embodied Energy (EE) refers to the energy consumption related either directly or indirectly to the building



facility, like material production, facility construction, maintenance, replacement, demolition, recovery of each material involved in the building.

1.1 Embodied energy and embodied CO₂ emissions

Three main stages can be distinguished during the life time of a building; the initial stage concerning the period of time from the beginning of its construction till the moment it becomes operational, the period of time that the building is operational (normally this is the more lasting period) and the final stage concerning demolition of the building and removal of its materials. EE of a building is accumulated along with time during the above three stages of its life. The energy consumed during the first stage is the Initial EE (IEE), the energy consumed during the operational stage of the building is the Recurrent EE (REE) and the energy consumed during the third stage of its life is the Demolition EE (DEE). This fact is expressed by the following equation:

$$EE = IEE + REE + DEE \quad (1)$$

IEE consists of two parts, namely the energy consumed directly (IEE_D) for the construction of building facility on site for construction, fabrication, transportation and administration and the energy consumed indirectly (IEE_I) upstream these activities for the production of all the required materials. REE concerns the energy that will have been consumed for the construction, materials, processes and equipment related to maintenance/replacement and retrofit/refurbishment actions during the operational period of the building facility. Demolition EE concerns the energy that will have been consumed for the demolition of the facility, transportation of materials off site, their recycling/reuse and the relevant administration after the end of its life. Like IEE, each of the other two terms, namely REE and DEE consists of two parts, one concerning direct EE and one concerning indirect EE [4]. The direct parts refer to energy consumed on site by equipment, tools, etc or to transport materials and products to the site, while the indirect parts refer to energy consumed to acquire process and manufacture the materials involved at the corresponding stage. Taking the above into account, equation (1) now becomes

$$EE = (IEE_I + IEE_D) + (REE_I + REE_D) + (DEE_I + DEE_D) \quad (2)$$

According to equation (2), EE can be separated in direct (IEE_D+REE_D+DEE_D) and indirect (IEE_I+REE_I+DEE_I) amounts of energy. From the six terms appearing in equation (2), the second one IEE_D is the one concerning on site construction of the building facility. The term left of it concerns energy consumed upstream this activity, while the terms to the right concern energy consumed (or to be consumed) downstream (with respect to time).

A companion concept concerning the environmental impact of Embodied Energy is that of the embodied carbon emissions or Embodied CO₂ (ECO₂), defined for each of the EE terms defined above, to be the corresponding amount of CO₂ emissions to the atmosphere. In this context, the life cycle CO₂ of the building is defined to be the CO₂ quantity corresponding to the life cycle EE of the building.

According to the literature [5], [6], the two basic categories of methods for calculating EE rely either on the Process Analysis or the Input-Output (IO) Analysis. Each of them has its own pros and cons [4], so Hybrid Analysis methods have been proposed in order to combine the advantages of both approaches and facilitate more comprehensive and accurate analysis. Furthermore, hybrid analysis has been proposed in the forms of process-based and IO-based hybrid analysis [4].

Unfortunately, independent the method of analysis used, EE databases suffer from problems of variation and incompatibility. According to [3], most of the previous studies either followed the International LCA standards, or they did not follow any standards, so the authors refer to the necessity of the development of a global database and compiled a list of parameters, mostly local, that are responsible for the lack of a global database. Such parameters are the methods of EE estimation, the building design, the construction methods, the kind and quantity of the constructive materials, the system boundaries or the geographical locations.

1.2 Previous and present work

In previous works by the first author, the focus was placed on the Initial indirect EE (IEE_i) of the materials and equipment comprising typical Hellenic dwellings. In these works, the constitutive materials met in such a building were classified in two main categories; the Electro-Mechanical Installations (EMI) and the Civil Engineering Materials (CEM). In [7], [8], [9] the EE of the EMI items were estimated for typical Hellenic dwellings, while in [10] similar work has been conducted for the CEM of typical Hellenic buildings.

In order to estimate the total EE and the related ECO_2 emissions of a whole building or even a component of it, a good material analysis is necessary. In all the above mentioned works, the material analysis, i.e. the breakdown of the set of items under consideration (mechanical or civil engineering) in their constitutive materials was the first step. The calculation of their corresponding masses was the second step, while at a third step, their EE / ECO_2 were obtained by multiplying mass values by the corresponding EE / ECO_2 coefficients of the materials. Although, these coefficients are nationally dependent parameters, available values from the open literature were used [11], since there is lack of a comprehensive Hellenic database. Although not being a rigorous approach, it provides the capability to obtain important practical results for initial guidance.

Since the coefficients used by [11] rely on process analysis, such an approach suffers from truncation errors [6]. The latter are related to the definition of the method boundary. Among the issues that are missing in such a procedure is to take into account the energy required for the manufacturing of the main compound items. Such an item is for example, the boiler in the EMI set. In the previous works, the contribution of the boiler to the IEE concerned the value corresponding to the energy contained per kg for each of its constitutive materials. However, in order to have a finished product in the form of a complete boiler, energy was also consumed in its production line and this contribution was missing. The assessment of the latter part is the objective of the present work.

In the present work, the focus is on the indirect EE of central heating boilers as a standard appliance of building services. This EE is considered as a sum of two terms, namely the EE concerning the production of materials constituting the boiler (EE_{MP}) and the EE concerning the manufacturing process of the boiler in its production line at the boiler construction house (EE_{MFG}). There are some works in the literature referring for example to the manufacturing energy of various products [12] or the derivation of metrics for product assembly and equipment [13]. The three-step methodology mentioned in the previous section is used herein to calculate EE_{MP} . Regarding the second term, this is calculated by estimating the energy consumption at each process of the production line. A way to accomplish this is by multiplying the nominal electrical power of the machine used at each stage by the corresponding average processing time.

In the light of the above, the present work focuses on the energy consumed for the manufacturing of typical domestic central heating boilers. The aim is to assess the contribution of this kind of energy to the overall EE by comparing it with the energy concerning the production of the constitutive boiler materials. Some standard oil/gas boilers, either made by steel or cast iron, as well as an autonomous compact boiler unit are studied. Their EE_{MP} and EE_{MFG} values are calculated and compared each other. Benchmark energy values concerning the manufacturing process of typical central heating boilers in Greece are extracted and their significance in terms of contribution in EE is assessed. Conclusions are made and future research directions are described.

2. Methodology - Test cases

In order to calculate the energy consumed for the production of materials used to construct a boiler (EE_{MP}), a three-step methodology [9] is implemented. According to this, the first step is a material analysis, i.e. the breakdown of the product under consideration to its constitutive single materials. The calculation of the corresponding masses was the second step, while at a third step, EE and ECO_2 values were obtained by multiplying mass values by the corresponding EE and ECO_2 coefficients of the materials. Although, these coefficients are nationally dependent parameters, available values from the open literature were used [11], since there is lack of a comprehensive Hellenic database. Since the coefficients used by [11] rely on process analysis, such an approach suffers from truncation errors [6];

the latter are related to the definition of the method boundary. So, although not being a rigorous approach, it provides the capability to obtain important practical results for initial guidance.

On the other hand, in order to calculate the energy consumed for the manufacturing of a boiler (EE_{MFG}), its production line is analyzed to stages. At each stage, this energy is estimated by means of multiplying the nominal power of the machine used by the average processing time. The required information can be either estimated by examining the production line at the boiler house or directly provided by the manufacturers. Electrical energy so obtained, is then transformed to primary energy for the sake of compatibility with EE concerning material production. According to the national regulation in Greece, the conversion factor that is used (in energy performance of buildings) to calculate primary energy from final energy use is 2.9 for electricity.

Similarly, the CO_2 emissions due to EE_{MP} will be denoted by $ECO_{2,MP}$, while that due to EE_{MFG} will be denoted by $ECO_{2,MFG}$. $ECO_{2,MP}$ values are computed by the same three-step methodology mentioned above for EE_{MP} , where the corresponding ECO_2 coefficients [11] are used. $ECO_{2,MFG}$ values are computed by the EE_{MFG} values (in kWh_e) and the fact that, according to the national regulation (in energy performance of buildings), the conversion factor to calculate CO_2 emissions from final energy use is $0.989 \text{ kgCO}_2/kWh_e$ for electricity.

Central heating boilers are generally classified to three categories according to their heating power, namely small boilers ($<50 \text{ kW}_h$), medium boilers ($50\text{--}400 \text{ kW}_h$) and large boilers ($>400 \text{ kW}_h$). Furthermore, according to their main material of construction, they are classified to steel boilers and cast iron boilers. Three steel boilers and three cast iron boilers are studied herein. All of them are gas/oil central heating boilers. Independent their material of construction, the three of them are small boilers, while the other three are medium ones.

Table 1 presents the six boilers selected herein as test cases and the names to be used for them.

Table 1 Typical small and medium size central heating boilers.

Case	Boiler Type	Heat Rate [kW_{th}]	Size
B1	Steel oil-gas boiler	67.7	Medium
B2	Steel oil-gas boiler	46.7	Small
B3	Steel oil-gas unitary unit	35.0	Small
B4	Cast iron oil-gas boiler	67.7	Medium
B5*	Cast iron oil-gas boiler [14]	60.0	Medium
B6*	Cast iron oil-gas boiler [15]	35.0	Small

*Only for the calculation of energy for material production (EE_{MP}) (no data for manufacturing, EE_{MFG}).

To obtain the required information, in order to estimate the energy consumption at each stage of the production line, as well as to analyze boilers B1-B4 to their constitutive materials, two boiler construction houses in Athens (Greece) were visited and the relevant information was recorded. Details on the description of the production line and the processes taking place, as well as the calculation of the manufacturing energy are described in [16].

3. Results and discussion

In what follows, results are presented concerning the two parts of embodied energy under consideration herein, namely EE_{MP} and EE_{MFG} , as well as the corresponding results for ECO_2 . It is reminded that, according to Table 1, among the six cases studied, B1, B2, B3 are steel boilers, while B4, B5, B6 are cast iron boilers.

3.1 Material production EE and ECO_2

Based on the information by the manufacturers, each of the four boilers B1-B4 was analyzed to its constitutive materials. The corresponding masses were calculated and then transformed to embodied energy and emissions. In addition, corresponding results for two more boilers presented in [14], [15] are also presented.

Table 2 presents the average contribution of the main materials used for steel and cast iron boilers (right), in terms of mass, EE and ECO_2 . These data have been extracted from the corresponding data concerning each of the six boilers B1-B6. Due to the fact that similar results concerning steel boilers were obtained and the same happened for the cast iron ones, it was decided to present herein averaged values for each of the two kinds of boilers.

Table 2 Average contribution in terms of mass, EE and ECO_2 of the main materials used for steel boilers (left) and cast iron boilers (right).

Steel boilers (B1, B2, B3)				Cast iron boilers (B4, B5, B6)			
Material	Mass [%]	EE [%]	ECO_2 [%]	Material	Mass [%]	EE [%]	ECO_2 [%]
Steel	94.1	94.9	95.6	Cast iron	92.1	85.4	89.2
Cement	4.8	1.0	2.3	Steel	1.1	1.1	1.0
Plastic	0.9	2.9	1.3	Cement	0.2	0.0	0.1
Aluminum	0.2	1.2	0.9	Plastic	1.0	2.9	1.3
				Aluminum	0.0	0.1	0.1
				Copper	5.0	8.8	7.4
				PEF	0.6	1.6	0.9

According to Table 2, it is obvious that steel and cast iron are the dominant materials in terms of mass, EE and ECO_2 , since they are the main construction material in each boiler kind. Steel contributes with about the 95% of the total in the three quantities in case of steel boilers. Cement is the second material in terms of mass contribution in steel boilers. Copper is ranked second in cast iron ones. The EE and ECO_2 contribution of the various materials are generally different from their mass contribution. This is due to the fact that materials participating in low quantities may have great EE coefficient, like for example in the cases of aluminum, copper and plastic. It should be marked that the EE coefficients are expressed in terms of primary energy [MJ_p].

Table 3 presents EE results concerning material production for each of the typical boilers studied herein. Apart from absolute values, energy values normalized by the boiler mass and the boiler heat rate are also provided. According to this table, it is interesting to notice that EE_{MP} is about 24 times the boiler mass in case of steel boilers or 27 times in case of cast iron boilers (thus an average of 25 independent the kind of boiler). This is rather logical, since in both kinds of boilers, there is one dominant material. Concerning EE_{MP} as a function of the boiler heat rate, it can be noticed that as the heat rate becomes lower the ratio $\text{EE}_{\text{MP}}/\text{Heat Rate}$ becomes greater, meaning that EE_{MP} does not scale with heat rate. The average values are about $60 \text{ MJ}_p/\text{kW}_{\text{th}}$ for steel boilers and about double $122 \text{ MJ}_p/\text{kW}_{\text{th}}$ for cast iron boilers.

Table 3 EE_{MP} for typical steel and cast iron boilers.

Case	Heat Rate [kW_{th}]	Mass [kg]	EE_{MP} [MJ_p]	$\text{EE}_{\text{MP}}/\text{Heat Rate}$ [$\text{MJ}_p/\text{kW}_{\text{th}}$]	$\text{EE}_{\text{MP}}/\text{Mass}$ [MJ_p/kg]
B1	67.7	202	4826.6	71.3	23.9
B2	46.7	88.3	2124.3	45.5	24.1
B3	35.0	92.9	2235.6	63.9	24.1
Average				60.2	24.0
B4	67.7	313	7847.8	115.9	25.1
B5	60.0	218	6118.3	102.0	28.1
B6	35.0	185.7	5214.5	149.0	28.1
Average				122.3	27.1

Table 4 presents ECO_2 results concerning material production for each of the typical boilers studied herein. Absolute, as well as normalized CO_2 values by the boiler mass and heat rate are also provided.

According to this table, the ratio of $\text{ECO}_{2,\text{MP}}$ to the boiler mass is 1.7 for steel boilers and 2 in the case of cast iron boilers. Average values of the $\text{ECO}_{2,\text{MP}}$ to heat rate ratio are about $4.4 \text{ kgCO}_2/\text{kW}_{\text{th}}$ for steel boilers and about double $8.9 \text{ kgCO}_2/\text{kW}_{\text{th}}$ for cast iron boilers.

Table 4 $\text{ECO}_{2,\text{MP}}$ for typical steel and cast iron boilers.

Case	Heat Rate [kW_{th}]	Mass [kg]	$\text{ECO}_{2,\text{MP}}$ [kgCO_2]	$\text{ECO}_{2,\text{MP}}/\text{Heat Rate}$ [$\text{kgCO}_2/\text{kW}_{\text{th}}$]	$\text{ECO}_{2,\text{MP}}/\text{Mass}$ [kgCO_2/kg]
B1	67.7	202	352.9	5.2	1.7
B2	46.7	88.3	153.6	3.3	1.7
B3	35.0	92.9	161.8	4.6	1.7
Average				4.4	1.7
B4	67.7	313	596.0	8.8	1.9
B5	60.0	218	438.1	7.3	2.0
B6	35.0	185.7	373.2	10.7	2.0
Average				8.9	2.0

3.2 Manufacturing EE and ECO_2

The information concerning boilers B1-B4 and required to calculate the energy consumption at each stage of their production line was obtained by two different boiler construction houses in Athens. An example of such information and the relevant calculation of the electrical energy required for the manufacturing of boiler B3 is provided in Table 5. As mentioned in a previous section, the total electrical energy has to be transformed to primary energy [MJ_p] for the sake of compatibility with the EE related to the production of materials.

Table 5 Electrical energy required for the manufacturing of boiler B3.

Process machine	Time [min]	Power [kW]	Electrical Energy [kWh_e]
Metal cutter	7.4	12	1.5
Cord positioning	3.7	5	0.3
Cylinder	8.3	10	1.4
Press	1.5	6	0.2
Rotating shears	5.2	5	0.4
Welding	10	150	25.0
Bending	6	21	2.1
Total			30.9

Table 6 presents EE results concerning manufacturing for each of the four boilers B1-B4, for which data were made available. According to this table, EE_{MP} is 2.1 times the boiler mass in case of steel boilers or 0.7 times in case of cast iron boilers. In addition, average values of the ration $\text{EE}_{\text{MP}}/\text{Heat Rate}$ are about $5.6 \text{ MJ}_p/\text{kW}_{\text{th}}$ for steel boilers and about $3.2 \text{ MJ}_p/\text{kW}_{\text{th}}$ for cast iron boilers.

Table 6 EE_{MFG} for typical steel and cast iron boilers.

Case	Heat Rate [kW_{th}]	Mass [kg]	EE_{MFG} [MJ_p]	$\text{EE}_{\text{MFG}}/\text{Heat Rate}$ [$\text{MJ}_p/\text{kW}_{\text{th}}$]	$\text{EE}_{\text{MFG}}/\text{Mass}$ [MJ_p/kg]
B1	67.7	202	340.6	5.0	1.7
B2	46.7	88.3	114.1	2.4	1.3
B3	35.0	92.9	322.1	9.2	3.5
Average				5.6	2.1
B4	67.7	313	217.1	3.2	0.7

Table 7 presents ECO_2 results concerning manufacturing for each of the four boilers B1-B4. The ratio of $\text{ECO}_{2,\text{MP}}$ to the boiler mass is 0.2 for steel boilers and 0.1 in the case of cast iron boilers. Average values of the $\text{ECO}_{2,\text{MP}}$ to heat rate ratio are about $0.5 \text{ kgCO}_2/\text{kW}_{\text{th}}$ for steel boilers and about double $0.3 \text{ kgCO}_2/\text{kW}_{\text{th}}$ for cast iron boilers. Opposite to what happens with the EE_{MP} values per unit heat rate or mass, where cast iron boilers had double value compared to steel ones, in the case of EE_{MFG} per unit heat rate or mass, cast iron boilers have about the half value compared to steel ones.

Table 7 $\text{ECO}_{2,\text{MFG}}$ for typical steel and cast iron boilers.

Case	Heat Rate [kW_{th}]	Mass [kg]	$\text{ECO}_{2,\text{MFG}}$ [kgCO_2]	$\text{ECO}_{2,\text{MFG}}/\text{Heat Rate}$ [$\text{kgCO}_2/\text{kW}_{\text{th}}$]	$\text{ECO}_{2,\text{MFG}}/\text{Mass}$ [kgCO_2/kg]
B1	67.7	202	32.3	0.5	0.2
B2	46.7	88.3	10.8	0.2	0.1
B3	35.0	92.9	30.5	0.9	0.3
Average				0.5	0.2
B4	67.7	313	20.6	0.3	0.1

3.3 Overall EE and ECO_2 results

Table 8 summarizes EE_{MP} and EE_{MFG} for the four typical steel and cast iron boilers studied above. Two quantities are computed for each boiler, namely the ratio of the boiler mass to heat rate and the ratio of EE_{MFG} to EE_{MP} . Average mass to heat rate is $2.5 \text{ kg}/\text{kW}_{\text{th}}$ in average for steel boilers, while in case of cast iron ones this is greater, with a value $4.625 \text{ kg}/\text{kW}_{\text{th}}$. The EE related to manufacturing is about the 9% of the EE related to production of the boiler materials for steel boilers, while this is lower, about 3%, in case of cast iron boilers.

Table 8 EE_{MP} and EE_{MFG} for typical steel and cast iron boilers.

Case	Heat Rate [kW_{th}]	Mass [kg]	Mass/ Heat Rate [$\text{kg}/\text{kW}_{\text{th}}$]	EE_{MP} [MJ_p]	EE_{MFG} [MJ_p]	$\text{EE}_{\text{MFG}}/\text{EE}_{\text{MP}}$
B1	67.7	202	3.0	4826.6	340.6	0.07
B2	46.7	88.3	1.9	2124.3	114.1	0.05
B3	35.0	92.9	2.7	2235.6	322.1	0.14
Average			2.5			0.09
B4	67.7	313	4.6	7847.8	217.1	0.03

Table 9 summarizes absolute and normalized values of $\text{EE}=\text{EE}_{\text{MP}}+\text{EE}_{\text{MFG}}$ for typical steel and cast iron boilers. According to it, the EE of a steel boiler (in MJ_p) can be estimated multiplying its heat rate (in kW_{th}) by 65.8. In case of a cast iron boiler, the corresponding multiplier is about the half (119 $\text{MJ}_p/\text{kW}_{\text{th}}$). Alternatively, and perhaps more reliably, the EE of a boiler (in MJ_p), either steel or cast iron, can be estimated multiplying its mass (in kg) by an average value of 26.

Table 9 Values of $\text{EE}=\text{EE}_{\text{MP}}+\text{EE}_{\text{MFG}}$ for typical steel and cast iron boilers.

Case	EE [MJ_p]	EE/Heat Rate [$\text{MJ}_p/\text{kW}_{\text{th}}$]	EE/Mass [MJ_p/kg]
B1	5167.2	76.3	25.6
B2	2238.4	47.9	25.3
B3	2557.7	73.1	27.5
Average		65.8	26.2
B4	8064.9	119.1	25.8

Table 10 summarizes absolute and normalized values of $\text{ECO}_2=\text{ECO}_{2,\text{MP}}+\text{ECO}_{2,\text{MFG}}$ for typical steel and cast iron boilers. According to it, the ECO_2 of a steel boiler (in kgCO_2) can be estimated multiplying its heat rate (in kW_{th}) by 4.9. In case of a cast iron boiler, the corresponding multiplier is

about double ($9.1 \text{ kgCO}_2/\text{kW}_{\text{th}}$). Alternatively, and perhaps more reliably, the ECO_2 of a boiler (in kgCO_2), either steel or cast iron, can be estimated multiplying its mass (in kg) by a value of about 2.

Table 10 Values of $\text{ECO}_2 = \text{ECO}_{2,\text{MP}} + \text{ECO}_{2,\text{MFG}}$ for typical steel and cast iron boilers.

Case	ECO_2 [kg]	$\text{ECO}_2/\text{Heat Rate}$ [kg/kW _{th}]	ECO_2/Mass [kg/kg]
B1	385.2	5.7	1.9
B2	164.4	3.5	1.9
B3	192.3	5.5	2.1
Average		4.9	1.9
B4	616.6	9.1	2.0

4. Conclusions – Future work

Several central heating boilers for Hellenic dwellings were studied. By utilizing data that were kindly made available from two boiler construction houses, the initial indirect Embodied Energy (EE) and Embodied ECO_2 (ECO_2) emissions were calculated. These data refer to the main constitutive materials of the boilers, as well as to the manufacturing stages along their production line. The mass quantities of the materials were used to estimate the part of EE concerning the production of the materials used for the construction of the boiler (EE_{MP}). The data related to the stages in the production line were used to estimate the part of EE concerning the manufacturing of the boiler as a finished product (EE_{MFG}). Correlations of these EE values, as well as of the corresponding ECO_2 values, with the heat rate and mass of the boiler were searched and relevant benchmark values were extracted for both steel and cast iron boilers. The practical utility of such values could be the estimation of the EE and ECO_2 quantities of a boiler by means of knowing its heat rate (e.g. from the heating technical study of the building) in order to be utilized in the context of Life Cycle Assessment of the building. As a continuation to this research, it is planned to apply similar studies in a greater range of boilers (heat rates, boiler houses, etc) in order to assure or modify the benchmark values found herein.

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