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Condensing boilers and variable speed pumps as a refurbishment option for heating systems in residential buildings - Energy and economic evaluation

K T Papakostas and F Pitsavou

Mechanical Engineering Department, School of Engineering, Aristotle University of Thessaloniki, EL 54124, Thessaloniki, Greece

E-mail: dinpap@eng.auth.gr

Abstract. This paper studies the energy and economic impacts from the replacement of a high-temperature hydronic heating system, consisting of an oil-fired conventional boiler and constant-speed circulator, by a low-temperature system with gas-fired condensing boiler and electronically controlled variable speed pump, in a residential building. Five case studies, which are categorized by the overall thermal insulation of the building and by the installed heating system, are examined in each of the two largest towns in Greece, namely Athens and Thessaloniki. In each study, the central heating system is designed and the thermal and electrical energy consumption is estimated by simulating the system according to the Bin method. Additionally, the operating cost, the cost of replacing the heating system, and the payback period of the investment are calculated. In the cases analysed, without any thermal insulation upgrade, the annual reduction of the thermal energy requirements varies from 26 to 29%. By upgrading the thermal insulation, thermal energy savings vary from 40 to 84%, depending on the previous insulation level of the building. With the use of variable speed circulators, electrical energy savings exceed 87% in all case studies. The fuel and electricity cost savings (prices of 2016) vary from 37 to 51%.

1. Introduction

Global energy consumption has increased significantly over the last 50 years as a result of the economic and population growth. Energy use in buildings is a major part of both global and national energy demand. In 2010, the building sector accounted for almost 32% of the world's final energy demand (24% for residential and 8% for commercial) and 30% of CO_2 emissions associated with energy use [1]. In the European Union (EU), in 2012, buildings accounted for around 40% of total final energy consumption, 55% of electricity consumption and almost 36% of the total CO_2 emissions [2]. Buildings are the largest end-use sector, followed by transport (32%), industry (26%) and agriculture (2%). In 2013, space heating in the EU-28 accounted for 69% of total household production, followed by domestic hot water for 11% [3]. Particularly in Greece, the residential sector was responsible for 26.6% of the total final energy consumption in 2015 [4].

It is obvious that the energy used in the building sector dominates all other end users. Moreover, nowadays the energy consumption for heating, ventilation and cooling in buildings, and consequently the greenhouse gas emissions, is of high importance due to the increasing demands for better thermal comfort conditions and the widening of people's living time in indoor spaces. This growth in energy consumption and CO_2 emissions in the building environment compelled most countries to promote energy efficiency and saving strategies as a priority in their energy policies. New building standards, codes, regulations, technical guidelines and legislation, as well as new energy efficient technologies are adopted to promote low energy consumption and sustainability, and thus to decrease the energy demands for heating and air-conditioning in buildings and consequently to minimize CO_2 emissions. In 2009 the EU, following the Kyoto Protocol of 1997, committed to reducing greenhouse gas (GHG) emissions and imposed the implementation of the 2020 climate change and energy targets, known as 20-20-20 targets, in order to reverse climate change and save energy. The three objectives to be reached by 2020 are (i) reducing GHG emissions by at least 20% compared with 1990 levels, (ii) increasing the share of renewable energy in final energy consumption to 20%, and (iii) moving towards a 20% increase in energy efficiency by reducing the use of primary energy. In order to achieve these targets, a series of directives and implementing regulations were adopted by the EU, with direct application in all its Member States.

Because of high-energy saving potentials, the building sector has become one of the priority areas to meet the EU's targets for 2020. In September 2015, the EU introduced the Energy-related Products (ErP) directive with the aim of annual energy savings from space and domestic water heating of about 1900 PJ by 2020, equivalent to about 110 Mt of CO_2 emissions (compared to what would happen if no measures were taken). According to this directive, all appliances for space heating, production and storage of hot water, as well as systems incorporating such devices, must meet certain EU energy-efficiency standards laid down by the EU and be consistent with the 20-20-20 objectives. The ErP Directive consists of two important parts: 1) the Ecodesign Directive [5] and Commission Regulations 813/2013 [6] and 814/2013 [7], which set minimum acceptable levels of energy efficiency and environmental requirements for water heaters with renewable energy sources, electric heaters, heat pumps and boilers with a rated thermal input ≤400 kW, and 2) the Energy Labelling Directive [8] and Commission Regulations 811/2013 [9] and 812/2013 [10], which impose a mandatory classification of each energy-related product in terms of energy consumption, noise level and other product-specific information. All products have to be sorted from A (higher efficiency) to G (lower efficiency). However, there are additional categories (A +, A ++ and A +++) that will be used for high efficiency products such as heat pumps.

By imposing restrictions on the power consumption of energy-related products, the ErP Directive stimulates manufacturers to create more efficient products, which will require less energy for their operation. In addition, the Directive excludes from the EU market all low performance products that do not have the necessary energy labelling and do not meet the Ecodesign directive requirements. According to the ErP directive, all conventional low efficiency boilers must be gradually replaced with condensing boilers or heat pumps. This means that from September 2015 it is prohibited for conventional boilers to enter the EU market and to be placed in heating installations, but the already existing ones will continue to operate until their end of life. Also, the use of circulators with energy class "A" and an energy efficiency index (EEI) of EEI≤0.23 becomes mandatory [11].

Following the above mentioned directives and regulations, two typical measures for improving a building's energy efficiency are the reduction of heating demands (by applying additional insulation on walls and replacing windows) and the decrease of the energy consumption of the heating system (by replacing the heat generator and the circulating pump with higher efficiency ones). In this study, the energy and economic benefits from the replacement of a high-temperature hydronic heating system (HTHS), consisting of an oil-fired conventional boiler and constant-speed circulator pump, by a low-temperature heating system (LTHS) with gas-fired condensing boiler and electronically controlled variable speed pump are assessed in a typical residential building. In particular, different study cases of increasing the heating system's efficiency, with or without refurbishment of the building envelope, are examined in the climatic conditions of the two largest cities of Greece, namely Athens and Thessaloniki. In each study case, the central heating system is designed, according to EN standards, and the energy consumption of the corresponding boiler (conventional or condensing) is estimated according to the Bin Method. Also, in each study case, the electrical energy consumption from the circulation pump (constant speed or electronically controlled variable speed) is also estimated.

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Thereafter, an economic impact analysis of the heating system's upgrade is performed, in which the operating cost, the cost of replacing the heating system, the payback period of the investment and the resulting economic benefit are calculated.

Various researchers have dealt with the subject of buildings' energy-efficiency upgrade, by taking envelope retrofit measures and by changing the operating conditions of the heating system. Matjaž Prek [12] presents a method for determining the new operation conditions of HTHS in retrofitted buildings, considering the energy savings, the thermal comfort conditions and the energy-efficient operation of the system. Arefeh Hesaraki et al. [13] presented LTHS from the perspective of the heat emitters and heat production. In their study, they showed that LTHS are more efficient and beneficial to use as compared with conventional heating systems, and that with their use carbon dioxide emissions are reduced. Qian Wang and Sture Holmberg [14] studied energy upgrade measures consisting of LTHS and ventilation retrofitting in a typical low-raise Swedish multi-family house built among 1965-1975. They showed that the proposed retrofitting strategy with LTHS + ventilation+ air-tightness renovation leads to higher thermal performance of the heating system and to 41% and 27% savings of heating and total primary energy, respectively. Renato M. Lazzarin [15] studied heating plant refurbishments in buildings and presented the advantages of installing condensing boilers with variable-speed pumps. The estimated payback period in two case studies was 8-10 years. Dan-Teodor Bălănescu and Vlad-Mario Homutescu did experimental work for improving the efficiency of condensing boilers [16]. Besides the energy and operating cost benefits, using a LTHS is also more sustainable due to a reduction in the generation of carbon dioxide. For every degree reduction of the supply temperature in a heating system, the carbon dioxide emission decreases by 1.6% [13].

2. Methodology

2.1. Building description - Study cases

The building under consideration is a three-storey block of flats with a flat roof, designed to resemble a typical residential building in Greece.

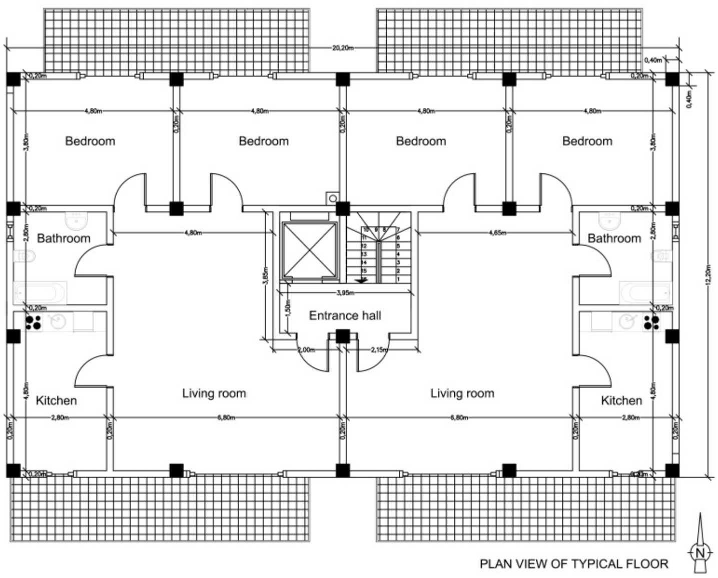

Figure 1. Plan view of the residential building typical floor.

It consists of 6 apartments (2 per typical floor), each of which has a net area of 103 m^2, and is considered to be fully heated in the living spaces. The two main elevations of the building are oriented to the north and to the south and the windows to wall ratio is 19%. The plan view of the typical floor is illustrated in figure 1. The building features a central heating system with hot water boiler and the heat is distributed in the rooms by hydronic radiators. Thermostatic control is provided in each apartment, with set temperatures of 20°C during daytime and a night setback at 18°C. Typical ventilation and infiltration values were considered, of 0.5 air change per hour for the main rooms, of 1.0 ach for the kitchen and of 1.5 ach for the sanitary rooms. The study was performed for the climatic conditions of the two largest cities in Greece, Athens and Thessaloniki, for three cases of thermal insulation and two heating systems with different operating conditions, a HTHS and a LTHS. The study cases are the following:

i. Building without thermal insulation – central heating system with an oil-fired conventional boiler sized and operating at high supply/return temperatures of 90/70°C
ii. Building which falls under the Greek Regulation for Building Insulation of 1979 – central heating system with an oil-fired conventional boiler operating at high supply/return temperatures of 90/70°C
iii. Building which falls under the Greek Regulation for Building Insulation of 1979 – central heating system with gas-fired condensing boiler sized and operating at low supply/return temperatures of 50/40°C
iv. Building which falls under the Greek Regulation for Energy Performance of Buildings of 2010 – central heating system with an oil-fired conventional boiler sized and operating at high supply/return temperatures of 90/70°C
v. Building which falls under the Greek Regulation for Energy Performance of Buildings of 2010 – central heating system with gas-fired condensing boiler sized and operating at low supply/return temperatures of 50/40°C.

2.2. Design of the heating system

The heating system's design process involves, among others, the calculation of the design heat loads, the selection of various devices such as radiators, boiler, burner, safety and balancing devices (expansion vessel, safety valve, two/three-way valves, thermostatic valves etc.), the pipe sizing, the calculation of the water pressure drop in the system, and finally the selection of the hot water circulator pump. This design process was applied in each of the above mentioned study cases.

2.2.1. Calculation of the design load, selection of devices

The design heat load of the building was calculated according to EN 12831 for each level of thermal insulation for both cities. The hydronic radiators in the case of oil-fired conventional boiler were selected for water supply/return/room temperatures 90/70/20°C, and in the case of the gas-fired condensing boiler for water supply/return/room temperatures 50/40/20°C respectively. Boilers were selected from heating equipment dealers and installers in the Greek market, by assuming an increase of 10% at the total design heat load. The design heat load of the building $\Phi_{HL,B}$, the boiler thermal load Q_K, the boiler thermal capacity Q_K' and the boiler efficiency η (according to the manufacturer's databooks) are given in table 1.

After calculating the above quantities, the replacement of the high-temperature (90/70°C) hydronic heating systems, consisting of oil-fired conventional boiler and constant-speed circulator pump, by low-temperature (50/40°C) systems with gas-fired condensing boiler and electronically controlled variable speed pump is examined. These study cases are:

A) Thermal upgrade of the building without thermal insulation to a building with insulation according to the Greek Regulation for Energy Performance of Buildings of 2010 in combination with retrofitting of the HTHS to a LTHS.
B) Retrofitting of the HTHS to a LTHS, in the building which is thermally insulated according to the Greek Regulation of 1979.
C) Thermal upgrade of the building with insulation according to the Greek Regulation of 1979 to a building which falls under the Greek Regulation for Energy Performance of Buildings of 2010 in combination with retrofitting of HTHS to a LTHS.
D) Retrofitting of HTHS to a LTHS, in the building which is thermally insulated according to the Greek Regulation for Energy Performance of Buildings of 2010.

Table 1. Design thermal load in [kW], boiler thermal load and boiler thermal capacity in [kW], and boiler efficiency for each study case.

Athens				Thessaloniki			
Building without thermal insulation – Oil-fired conventional boiler							
$\Phi_{HL,B}$ [W]	Q_K [W]	Q_K' [kW]	η [%]	$\Phi_{HL,B}$ [W]	Q_K [W]	Q_K' [kW]	η [%]
56682	62350	63	91.5	73253	80578	98	92.1
Building insulated according to Greek Regulation of 1979 – Oil-fired conventional boiler							
26292	28922	29	93.1	33507	36858	40.7	93.2
Building insulated according to Greek Regulation of 2010 – Oil-fired conventional boiler							
23026	25328	29	93.1	29683	32652	40.7	93.2
Building insulated according to Greek Regulation of 1979 – Gas-fired condensing boiler							
26292	28922	36.6	108	33507	36858	39	107.7
Building insulated according to Greek Regulation of 2010 – Gas-fired condensing boiler							
23026	25328	27.5	108	29683	32652	36.6	108

The refurbishment of the building envelope results in a decrease of the required heat for heating and the needed power of radiators. Nevertheless, there is a risk that LTHS may not be able to provide enough heat to maintain the required thermal comfort level in the living spaces, therefore it is required to change the heat emitters in the building to be adapted to the lower supply/return water temperatures. By examining the radiators' features in each study case, it is observed that although the building is upgraded in terms of thermal protection, through the transition from the HTHS into the LTHS, the power output of the radiators in their majority is not sufficient and a replacement with radiators of higher thermal power and larger size is needed. The only exception is the study case (A), in which some radiators are not required to be replaced.

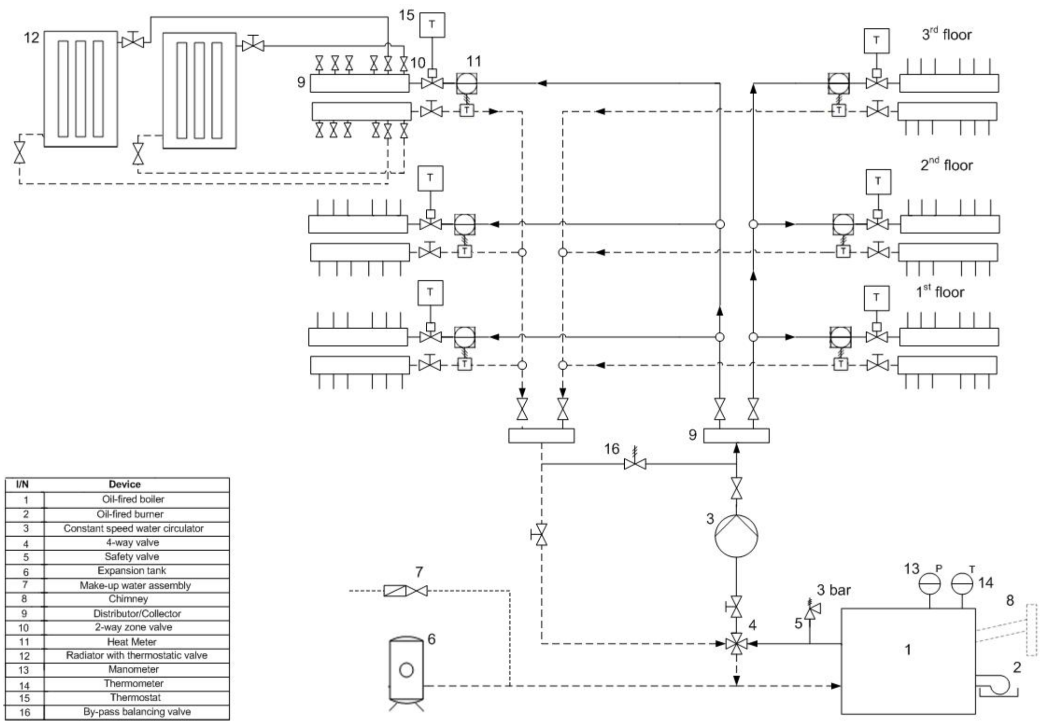

Figure 2. Radiators/piping/devices diagram of the high temperature water heating system (HTHS).

2.2.2. Pressure drop calculation, selection of circulation pump

Figure 2 illustrates the radiators/piping/devices diagram of the high water temperature heating system with an oil-fired conventional boiler.

The system is central, two-pipe, with panel type hydronic radiators. The hot water is supplied to the apartments by two vertical steel pipes and is driven to the supply collectors of each apartment, whereupon plastic pipes are started for each radiator. The return pipes drive the water to the return collectors and to the boiler. Each apartment has its own heating autonomy. A two-way valve with a thermostat and a heat meter is installed at the supply steel pipe of each apartment, while a four-way mixing valve is placed after the boiler. A constant-speed pump is used to provide the needed pressure in the hot water and circulation pipeline.

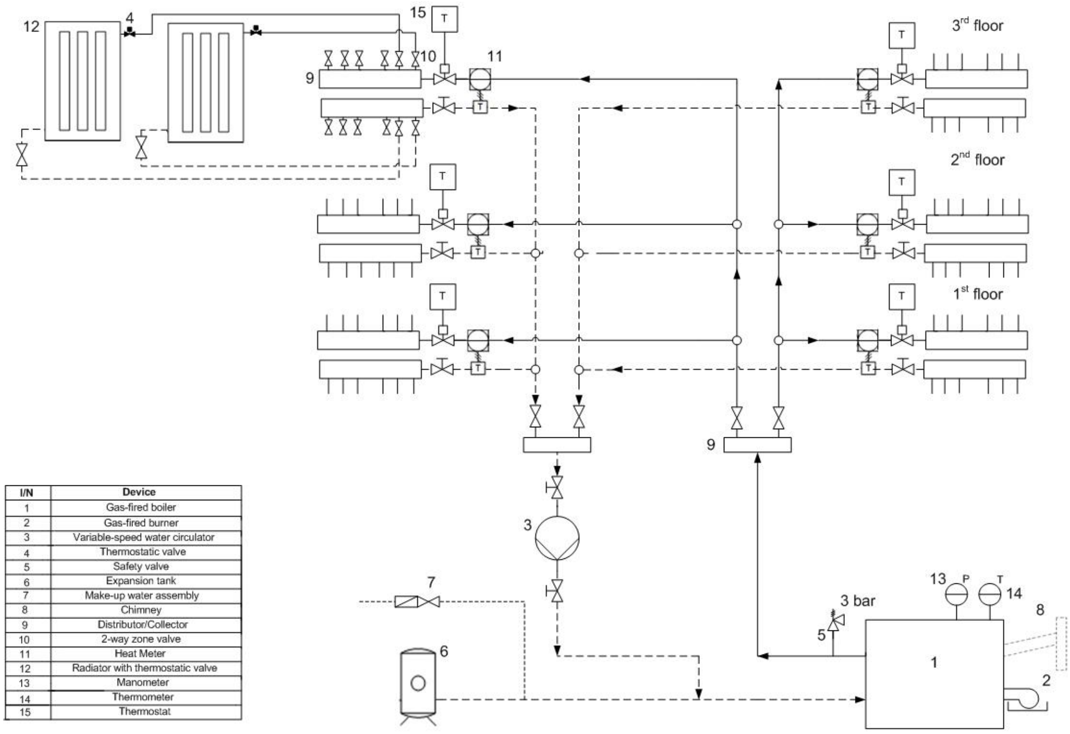

Figure 3. Radiators/piping/devices diagram of the low temperature water heating system (LTHS).

Table 2. Technical characteristics of the water circulators for each study case.

Athens				Thessaloniki			
Building without thermal insulation – Oil-fired conventional boiler							
V [m³/h]	H [m]	Speed [rpm]	P_1 [W]	V [m³/h]	H [m]	Speed [rpm]	P_1 [W]
2.71	2.14	2190	100	4.22	2.9	2500	205
Building insulated according to Greek Regulation of 1979 – Oil-fired conventional boiler							
1.25	0.96	1890	75	1.75	0.92	1650	125
Building insulated according to Greek Regulation of 2010 – Oil-fired conventional boiler							
1.25	0.96	1890	75	1.75	0.92	1650	125
Building insulated according to Greek Regulation of 1979 – Gas-fired condensing boiler							
3.15	1.74	1200÷4230	3÷40	3.36	2.5	1200÷3700	7÷120
Building insulated according to Greek Regulation of 2010 – Gas-fired condensing boiler							
2.37	1.43	1200÷4230	3÷40	3.15	1.84	1200÷3700	7÷120

The design concept of the low-temperature heating system, which is illustrated in figure 3, is quite the same but the four-way mixing valve is missed. The circulator pump is electronically controlled with variable speed, while thermostatic valves are installed on each radiator.

The sizing of the piping network for each of the five study cases as well as the calculation and selection of all the devices are given in detail in [17]. In table 2 all the technical characteristics (flow rate V, head H, speed, power consumption P_1) of the water circulators per study case are given.

Energy analysis

The energy consumption of the heating system per study case was calculated according to the Bin Method [18]. This method consists of performing instantaneous energy calculations at various different outdoor dry bulb temperature conditions and multiplying the results by the number of hours of occurrence of each condition. Usually, the outdoor temperature conditions are the midrange values of equal sized temperature intervals, which are called “bins”. This procedure can account for the part load performance of the heating equipment. According to the method, the heating requirements of a building are considered to be a linear function of the difference between the indoor and outdoor temperature. Heat gains by occupants, lights, devices and solar radiation are taken into account by considering as indoor temperature of the building the balance-point temperature θ_{bal}. Balance-point temperature is defined as the outdoor temperature at which, for a given internal building temperature θ_{int}, the total thermal losses of the building are equal to its thermal gains, namely as the outdoor temperature at which the building requires neither heating nor cooling.

2.3. Calculations procedure

The required bin data for both cities were obtained from [19]. For each temperature interval (bin), the energy required for heating the building $Q_{build}(\theta_j)$ in [Wh] is calculated as:

$$Q_{build}(\theta_j) = H_B \cdot DT(\theta_j) \cdot n_j \tag{1}$$

where θ_j is the midrange value of each temperature interval in [°C], H_B is the total heat loss coefficient of the building in [W/K], $DT(\theta_j)$ is the difference between the balance-point temperature of the building and the average value of the temperature bin interval $(\theta_{bal} – \theta_j)$ in [K], and n_j is the frequency of occurrence of each temperature interval in [h].

The balance-point temperature θ_{bal} is calculated as:

$$\theta_{bal} = \theta_{int} - \frac{Q_{gain}}{H_B} \tag{2}$$

where θ_{int} is the internal 24-hour weighted temperature of the building in [˚C], and Q_{gain} are the total heat gains of the building in [W] according to [18].

The calculations show that the balance-point temperature ranges from 17.65÷17.80˚C at the building without thermal insulation, from 15.3÷15.7˚C at the building which is thermally insulated according to the Greek Regulation for Building Insulation of 1979, and from 14.6÷15.1 ˚C at the building which falls under the Greek Regulation for Energy Performance of Buildings of 2010, depending on region and month of calculation. That is, as the thermal protection of the building is upgraded, its thermal capacity is increased, and the need for heating is appeared at lower outdoor temperatures. Analytical calculations are given in [17].

Since the efficiency of boilers depends on boiler load (ratio of heat load to boiler rated power) it is also necessary to calculate the partial load of the building in each temperature interval.

The heat load of the building in each temperature interval $\Phi_{HL,j}$ in [W], is given by the equation:

$$\Phi_{HL,j} = H_B \cdot (\theta_{int} - \theta_j) \tag{3}$$

while the partial heat load $\Phi'_{HL,j}$ [%] in each temperature interval is:

$$\Phi'_{HL,j} = \frac{100 \cdot \Phi_{HL,j}}{\Phi_{HL,B}}. \tag{4}$$

The fuel consumption FC in [l of oil] for the conventional boiler or in [m^3 of natural gas] for the condensing boiler is given by the equation:

$$FC(\theta_j) = \frac{Q_{build}(\theta_j)}{1000 \cdot H_o \cdot \eta_{total}} \quad (5)$$

where H_O is the calorific value of the fuel in [kWh/l] for oil and in [kWh/m^3] for natural gas, and η_{total} is the overall efficiency of the heating system,

$$\eta_{total} = \eta_{boiler} \cdot \eta_{dis,sys} \cdot \eta_{em} \quad (6)$$

where η_{boiler} is the efficiency of the boiler (in relation to the partial load), $\eta_{dis,sys.}$ The efficiency of the hot water distribution network, and η_{em} the efficiency of the terminal heating units according to [20].

2.4. Fuel and electricity consumption - operating costs

By applying the calculations procedure described above for the 5 different study cases of the paragraph 2.1, the boiler energy requirements Q (the ratio of building's energy requirements Q_{build} to the system's total efficiency η_{total}) in [kWh], the fuel consumption FC in [l or m^3], and the cost of fuel in [€] per study case were calculated. The energy analysis was also performed without taking into account the heat gains Q_{gain} in the thermal balance of the building, i.e. on the basis of the internal 24-hour weighted temperature of the building θ_{int}. In this case, the heating system is required to operate for a longer period because the operation starts at a higher outside temperature, as it applies $\theta_{int}>\theta_{bal}$. Since the balance-point temperature θ_{bal} is always calculated by making assumptions about the occupancy in the building, the use of devices and lights and the contribution of solar radiation to the thermal balance, which always imply some uncertainty, it was considered that it would be better to study both cases of energy analysis. The results are given in table 3 for both cases (in brackets are given the results of the energy analysis without the heat gains). Heating oil prices in [€/l] were taken from [21], for the period October 2015÷April 2016. Natural gas prices (with all taxes included) in [€/kWh] and calorific values in [kWh/m^3] for the given period were obtained from [22], [23].

Table 3. Energy requirements in [MWh], fuel consumption in [l or m^3] and fuel cost in [€] throughout the heating season per study case for Athens and Thessaloniki.

	No thermal insulation	Thermal insulation according to Greek Regulation of 1979		Thermal insulation according to Greek Regulation of 2010	
	Athens				
	Conventional boiler	Conventional boiler	Condensing boiler	Conventional boiler	Condensing boiler
Q [MWh]	113.0 (146.2)*	32.1 (62.7)	23.8 (44.5)	23.7 (53.6)	17.7 (38.0)
FC [l or m^3]	11301 (14624)	3213 (6273)	2044 (3816)	2372 (5362)	1520 (3262)
Cost [€]	9825 (12714)	2793 (5454)	1827 (3411)	2062 (4662)	1358 (2916)
	Thessaloniki				
Q [MWh]	162.9 (197.2)	47.2 (79.4)	34.6 (56.5)	36.1 (67.7)	26.5 (47.8)
FC [l or m^3]	16291 (19720)	4717 (7941)	3039 (4956)	3609 (6770)	2323 (4196)
Cost [€]	14029 (16982)	4062 (6838)	2032 (3313)	3108 (5830)	1504 (2717)

*Values in brackets have been calculated without the heat gains in the building

The calculation of the pumps electric power consumption PC was based on the power consumption P_1 given by the manufactures. For constant speed circulators, the power consumption is assumed to be constant throughout the system's operation and is equal to that given in table 2. For electronically controlled variable speed circulators, the power consumption varies according to the water mass flow

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rate. In this study, it was considered that the water mass flow is reduced proportionally to the heat load of the building and that the differential pressure of the circulator remains constant. The power consumption in [W] is calculated from the electronic application of the circulators manufacturer [24]. By multiplying the power consumption with the frequency of occurrence of each temperature interval n_j, the electricity consumption of the circulators PC in [Wh] is resulted, which is considered to be zero when there is no demand for heating. Electricity prices (with all taxes) were calculated according to [25]. Table 4 gives the electricity consumption and the cost of electricity for all study cases.

Table 4. Electricity consumption in [kWh_{el}] and electricity cost in [€] throughout the heating season per study case for Athens and Thessaloniki.

	No thermal insulation	Thermal insulation according to Greek Regulation of 1979		Thermal insulation according to Greek Regulation of 2010	
	Athens				
	Constant-speed circulator	Constant-speed circulator	Variable-speed circulator	Constant-speed circulator	Variable-speed circulator
PC [kWh_{el}]	421 (463)*	270 (374)	12 (20)	213 (374)	8 (13)
Cost [€]	143 (150)	116 (130)	71 (72)	106 (130)	70 (71)
	Thessaloniki				
PC [kWh_{el}]	922 (978)	510 (596)	61 (75)	443 (596)	55 (74)
Cost [€]	232 (242)	159 (174)	79 (82)	147 (174)	78 (82)

* Values in brackets have been calculated without the heat gains of the building

The results given in tables 3 and 4 show the great energy savings achieved by replacing conventional boilers and constant-speed circulators with more energy-efficient systems. More specifically, the annual reduction in thermal energy consumption with the installation of a LTHS in a building, without any thermal insulation upgrade (study case B) is 26% for Athens and 27% for Thessaloniki (the corresponding percentage without considering any heat gains in the building is 29% for both cities).

In cases where the building is thermally insulated according to the Greek Regulation for Energy Performance of Buildings of 2010 the thermal energy savings range from 44% for the study case C, to 84% for study case A, for both cities (the corresponding percentages for the calculations with no heat gains in the building are 40% and 75%). The use of a variable-speed circulator leads to energy savings that exceed the 87% in all cases (87 ÷ 98% depending on the studied case). Moreover, the economic benefit resulting from this replacement is high, so there are benefits not only for the environment but also for the cost of living.

2.5. Cost of new equipment – payback period

The cost of upgrading the heating system from a HTHS to a LTHS, in any study case (A-D), takes into account the cost of new radiators, the replacement of oil-fired conventional boilers with new of condensing technology, and the replacement of the constant-speed circulators with electronically controlled variable-speed ones.

The required changes in each case of upgrading of the heating system are described in detail in [17]. Table 5 shows the investment cost of replacements in each case of the heating system's upgrading. At this point, it should be noted that the extra cost of upgrading the thermal insulation of the building is not taken into account.

Table 5. Investment cost [€] for the energy upgrade of the heating system.

From/To	1979 Greek Regulation LTHS		2010 Greek Regulation LTHS	
	Athens			
HTHS	Cost of new radiators	Cost of new boiler/circulator	Cost of new radiators	Cost of new boiler/circulator
No thermal insulation	-	-	3605	2035
1979 Greek Regulation	6720	2335	5575	2035
2010 Greek Regulation	-	-	5575	2035
	Thessaloniki			
No thermal insulation	-	-	6282	2710
1979 Greek Regulation	8155	3955	7776	2710
2010 Greek Regulation	-	-	7776	2710

The payback period was calculated using the Simple Payback Method according to the equation:

$$Payback\ Period = \frac{Investment\ Cost}{Annual\ Income}. \qquad (7)$$

The *Annual Income* is defined as the difference in the cost of fuel consumption FC and power consumption PC (given in tables 3 and 4) before and after the energy upgrading of the building and the heating system. Table 6 gives the results of the “Annual Income” for each study case. The annual benefits are calculated for both cases: i) with energy analysis based on the balance-point temperature θ_{bal} and ii) with energy analysis without taking into account the building’s thermal gains (values in brackets in table 6). In the second case, obviously the benefit is higher because the heating system is operating for a longer period during the winter season, as explained previously.

Table 6. Annual Income [€] per study case of the heating system’s upgrading.

From/To	1979 Greek Regulation LTHS	2010 Greek Regulation LTHS
HTHS	Athens	
No thermal insulation	-	8540 (9879)
1979 Greek Regulation	1012 (2101)	1482 (2597)
2010 Greek Regulation	-	740 (1805)
	Thessaloniki	
	-	
No thermal insulation	2109 (3617)	12678 (14425)
1979 Greek Regulation	-	2559 (4122)
2010 Greek Regulation		

* Values in brackets have been calculated without the heat gains of the building

The payback periods for each case of the building’s upgrading are given in figure 4. But, according to the ErP Directive, all conventional boilers and constant-speed circulators should be replaced by condensing boilers and inverter circulators respectively at the end of their life cycle. If we consider as investment cost only the cost of the radiators (provided that the boiler and the circulator have to be replaced anyway), then the payback period is even lower. The Payback Period in this case is given in figure 5.

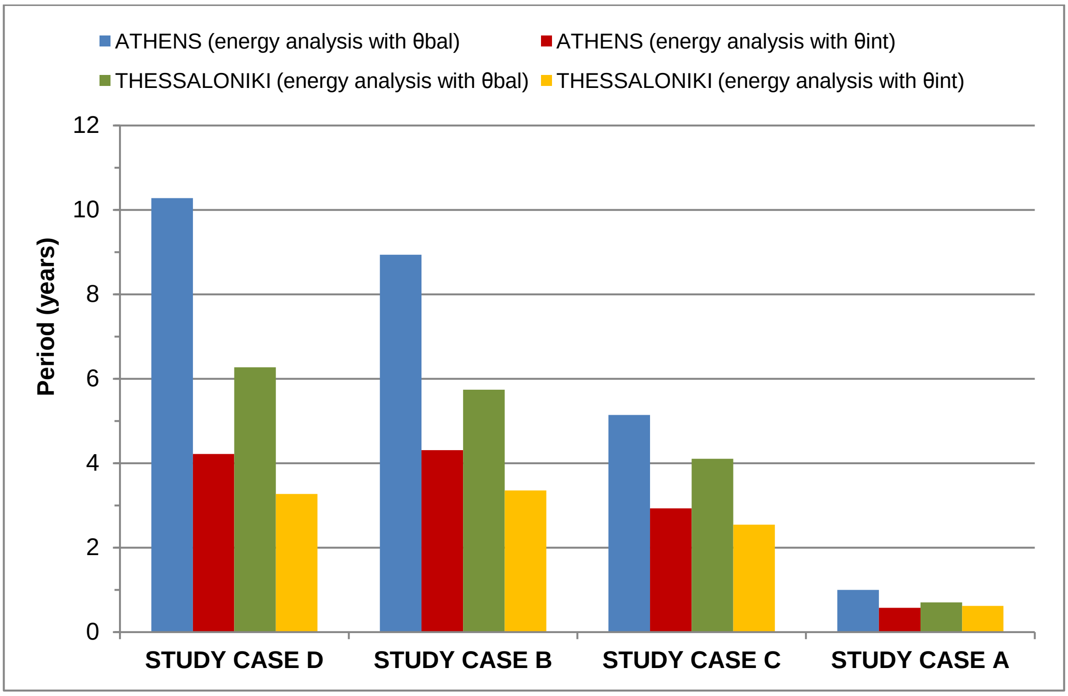

Figure 4. Payback period of the heating system's replacement for each study case.

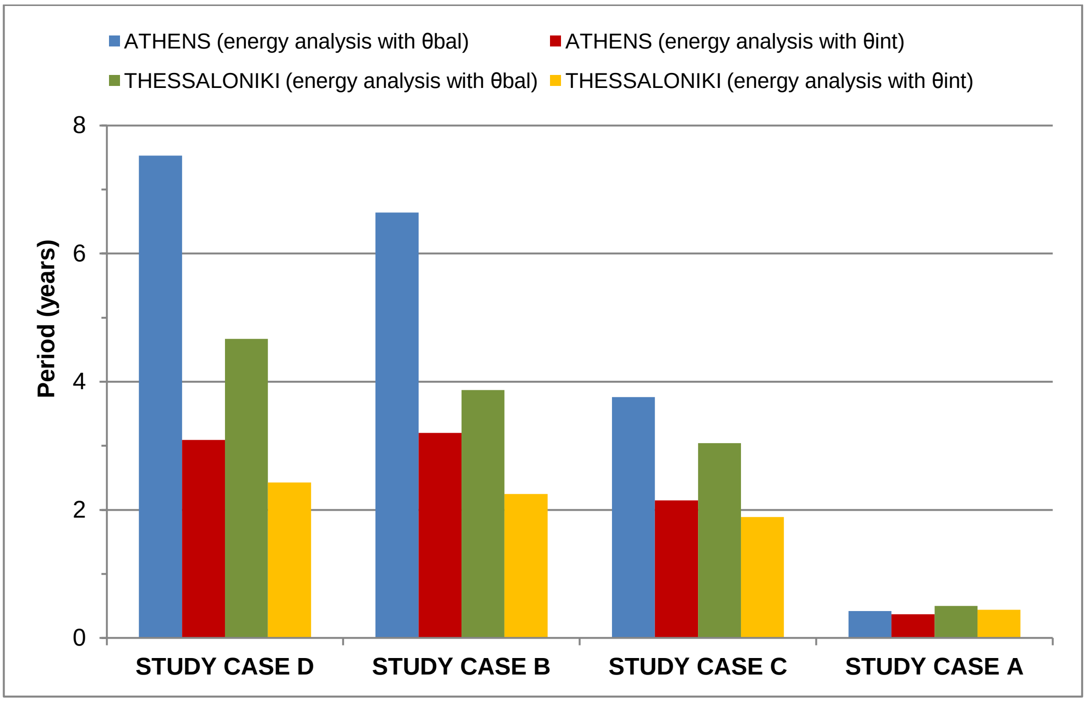

Figure 5. Payback period of the heating system's replacement for each study case (without taking into account the boiler's and the circulator's cost).

The payback period for the heating system's replacement in the case of building which falls under the Greek Regulation of 2010 (study case D) is 10.3 years in Athens and 6.3 years in Thessaloniki. In the case of a building with thermal insulation according to the 1979 Greek Regulation (study case B) the corresponding payback periods for the two cities are 9 and 5.7 years respectively. When the

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thermal protection of the building is upgraded from the 1979 Greek Regulation to the Regulation of 2010 (study case C), the payback period is less than 5 years for both cities, whereas in the case of the building without thermal insulation, which is energy upgraded according to the Regulation of 2010 (study case A), the payback period is less than one year. With an energy and economic analysis based on the 24-hour internal weighted temperature of the building θ_{int}, the payback periods of the heating system's upgrade are smaller in all study cases. In study cases B and D, the payback period is about 4.3 years in Athens while for Thessaloniki the corresponding period is about 3.3 years. When the thermal protection of a building is upgraded, the payback period is less than 3 years in study case C, for both cities, and less than one year in study case D.

Of course, as already mentioned, the second approach is theoretical because there are always some internal and solar heat gains which contribute to the thermal balance of the building. Since the results of every simulation procedure are just an approach of the real operation of a system, which depend to a large extent on assumptions from the system's operation, the behavior of the users and the accuracy of the data (climate, building, efficiency etc.), it could be assumed that the payback periods are between the results obtained with the two approaches for the building's heat gains. If it is considered that the investment cost includes only the cost of the radiators, then the payback period for Athens varies from 0.4 to 7.5 years, while for Thessaloniki from 0.5 to 4.5 years, depending on the study case. For an energy and economic analysis based on the internal weighted temperature of the building θ_{int}, the payback period is less than 3 years for all study cases. Here also, it can be assumed that the actual payback period is between the results according to the two approaches.

3. Conclusions

The implementation of the ErP Directive in hot water heating systems requires the transition from high temperature to low temperature systems, in which the heat source will be either a condensing boiler or a heat pump. Respectively, the installation of electronically controlled variable speed circulators is becoming also mandatory. In this paper, the energy and economic benefits of transforming a conventional high temperature central heating system with an oil-fired boiler and a constant speed circulator to a low temperature one with natural gas condensing boiler and variable speed circulator, in a typical residential building in Athens and Thessaloniki, are presented. The cases that have been studied are the heating system's replacement without upgrading the building's thermal protection and the replacement with upgrading the thermal protection according to the Greek Regulation for Energy Performance of Buildings of 2010.

The results show that the decrease in energy consumption, without upgrading the building's thermal insulation, is about 26% for both cities. In the cases where the building is thermally insulated, the energy conservation ranges from 44% for the building which falls under the Greek Regulation for thermal insulation of 1979 up to 84% for the building without thermal insulation. The use of a variable speed circulator leads to electricity savings ranging from 87 ÷ 98% depending on the study case. The savings in operating costs, i.e. in the cost of fuel and electricity, are proportional to the energy savings achieved in each study case. The annual cost reduction with the installation of a LTHS, without upgrading the thermal insulation of the building, is about 35% for Athens and 50% for Thessaloniki. When applying the Greek Regulation for Energy Performance of Buildings of 2010, the annual reduction in operating costs ranges in Athens from 51% for a building which falls under the 1979 Greek Regulation up to 86% for a building without thermal insulation. The corresponding values for Thessaloniki are 63% to 89%.

The payback period ranges from 3 to 10 years without upgrading the thermal protection of the building and from 1 to 5 years with upgrading (without taking into account the cost of thermal insulation), according to the study case. Of course, electricity and fuel prices, which are always characterized by some uncertainty as to their future behavior, determine the result to a significant extent.

4. References

[1] Ürge-Vorsatz D, Cabeza L F, Serrano S, Barreneche C and Petrichenko K 2015 Heating and cooling energy trends and drivers in buildings *Renewable and Sustainable Energy Reviews* **41** pp 85–98

[2] ODYSSEE-MURE 2015 Energy Efficiency Trends and Policies in the Household and Tertiary Sectors - An Analysis Based on the ODYSSEE and MURE Databases *Report from the ODYSSEE-MURE project co-funded by the Intelligent Energy Europe programme of the European Union*

[3] http://ec.europa.eu/eurostat/web/energy/data/main-tables (last accessed 16th.09.15)

[4] Eurostat Statistical books 2017 Energy balance sheets 2015 data (European Union)

[5] Directive 2009/125/EC of the European Parliament and of the Council 2009 Establishing a framework for the setting of ecodesign requirements for energy-related products *Official Journal of the European Union 31.10.2009* pp L 285/10–35

[6] Commission Regulation (EU) No 813/2013 Implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for space heaters and combination heaters *Official Journal of the European Union 6.9.2013* pp L 239/136–161

[7] Commission Regulation (EU) No 814/2013 Implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for water heaters and hot water storage tanks *Official Journal of the European Union 6.9.2013* pp L 239/162–183

[8] Directive 2010/30/EU of the European Parliament and of the Council 2010 On the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products *Official Journal of the European Union 18.6.2010* pp L 153/1–12

[9] Commission delegated Regulation (EU) No 811/2013 Supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of space heaters, combination heaters, packages of space heater, temperature control and solar device and packages of combination heater, temperature control and solar device *Official Journal of the European Union 6.9.2013* pp L 239/1–82

[10] Commission delegated Regulation (EU) No 812/2013 Supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of water heaters, hot water storage tanks and packages of water heater and solar device *Official Journal of the European Union 6.9.2013* pp L 239/83–135

[11] Commission Regulation (EC) No 641/2009 Implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for glandless standalone circulators and glandless circulators integrated in products *Official Journal of the European Union 23.7.2009* pp L 191/35–41

[12] Prek M 2017 Energy Efficiency of Hydronic Heating System in Retrofitted Buildings *Energy Efficient Buildings* (InTech) DOI: 10.5772/62592

[13] Hesaraki A, Ploskic A and Holmberg S 2015 Integrating Low-temperature Heating Systems into Energy Efficient Buildings *6th International Building Physics Conference IBPC 2015 Energy Procedia* **78** pp 3043 – 3048

[14] Wang Q and Holmberg S 2015 Combined Retrofitting with Low Temperature Heating and Ventilation Energy Savings *6th International Building Physics Conference IBPC 2015 Energy Procedia* **78** pp 1081 – 1086

[15] Lazzarin R M 2012 Condensing boilers in buildings and plants refurbishment *Energy and Buildings* **47** pp 61–67

[16] Bălănescu D T and Homutescu V M 2016 Experimental Study on the Combustion System Optimization in the Case of a 36 kW Condensing Boiler *10th International Conference Interdisciplinary in Engineering INTER-ENG 2016 Procedia Engineering* **181** pp 706-711

IOP Conf. Series: Materials Science and Engineering **444** (2018) 082001 doi:10.1088/1757-899X/444/8/082001

[17] Pitsavou F 2016 Heating systems with condensing boilers – Energy analysis in a residential building in Athens and Thessaloniki Diploma Thesis School of Mechanical Engineering Aristotle University of Thessaloniki (in Greek)
[18] ASHRAE Handbook - Fundamentals 1985 *American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc.* chap 26 (Atlanta Geo USA)
[19] Zagana Papavasileiou P 2013 Updating of temperature data base of Athens and Thessaloniki for energy studies - Period 1983-2012 Diploma Thesis School of Mechanical Engineering Aristotle University of Thessaloniki (in Greek)
[20] Technical Directive of the Technical Chamber of Greece 20701-1 2012 T.O.T.E.E. 20701–1/2010 Analytical Specifications of Parameters for the Calculation of the Energy Performance of Buildings and the Issue of Energy Certificate (In Greek) http://portal.tee.gr/
[21] Greek Ministry of Development and Competitiveness Weekly fuel prices bulletin 29/4/2016 http://www.fuelprices.gr
[22] Attiki Natural Gas Distribution Company EDA Attikis S.A. http://www.aerioattikis.gr
[23] Gas Distribution Company Thessaloniki –Thessalia S.A. https://www.edathess.gr/
[24] WILO Pioneering for You http://www.wilo.gr
[25] Public Power Corporation S.A. - Hellas (PPC) Residential Tariff-Γ1 https://www.dei.gr/en/oikiakoi-pelates/timologia