ENERGY AND ECONOMIC ANALYSIS OF AN AUDITORIUM'S AIR CONDITIONING SYSTEM WITH HEAT RECOVERY IN VARIOUS CLIMATIC ZONES

by

Konstantinos T. PAPAKOSTAS [*], Ioannis TIGANITIS, and Agis M. PAPADOPOULOS

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

In many heating, ventilation and air-conditioning (HVAC) applications, heat recovery devices are installed, aiming at reducing energy consumption. Especially in buildings requiring a high percentage of outside air for ventilation, there is a high potential for heat recovery from exhaust air. Climatic conditions are an important parameter which affects the recovered heat and the payback period of the heat recovery device. In this paper, a 250 person auditorium is used as a model to estimate the applicability of an air-to-air fixed-plate heat exchanger installed in the air handling unit of the HVAC system. The application is considered for four cities, representative of climatic zones A, B, C, D of Greece, which also represent typical Mediterranean climate conditions. Zone A, Crete and Southern Greece, is similar to Nicosia (Cyprus) and Palermo (Sicily), Zone B, with Athens, corresponds to Rome (Italy) and coastal Spain, Zone C with Thessaloniki is similar to the Toulon (France) and Split (Croatia) and Zone D, with its continental climate is more like Milan (Italy) and Lyon (France). An energy analysis with the modified bin method energy calculation was performed to calculate (a) the heating and cooling energy that can be recovered, (b) the reduction in HVAC equipment, and (c) the expected payback period. For the specific climatic conditions examined, it was proven that: heating energy consumption decreased by 31 to 40%, depending on occupancy, while electric energy consumption didn't change notably; the payback period does not exceed 24 months, depending on climate zone and occupancy.

Key words: *HVAC systems, heat recovery, air-to-air heat exchangers,*
           energy analysis, modified bin method

Introduction

The prime focus of HVAC systems in comfort applications is the control of temperature and humidity in occupied spaces and the supply of adequate ventilation, in order to create a comfortable and healthy indoor environment. The HVAC system typically accounts for much of the energy consumed in a building in the form of heat or electricity, for the operation of chillers, heat pumps, boilers, fans, pumps, and control devices. In ventilation systems serving spaces with high minimum requirements for outdoor airflow (for example, densely occupied spaces), the energy consumption for the outdoor fresh air treatment is usually high, while the exhaust air carries away a large fraction of the energy that is consumed. By recapturing the

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[*] Corresponding author, e-mail: dinpap@eng.auth.gr

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energy from the exhausted air, that would otherwise be lost, and by using it to precondition the incoming outdoor air the energy waste can be substantially reduced. Outdoor air preconditioning is the process of cooling, dehumidifying, heating and/or humidifying the entering outdoor air to approximately indoor temperature and humidity conditions. With the application of heat recovery (HR) technology for preconditioning the outdoor ventilation air, the air-conditioning and heating equipment can be downsized considerably and the energy consumed can be notably decreased.

There are several types of HR devices which are used for transferring energy from the exhaust air to the supply air or vice versa. Generally, they can be divided into two main categories: (a) the sensible energy recovery devices, which transfer only sensible heat, and (b) the total energy (sensible and latent) recovery devices, which transfer both sensible heat and moisture between the outdoor and the exhaust air. The first category includes fixed-plate heat exchangers, heat pipes, aqueous glycol coil loops, and sensible energy wheels; the most common example of the latter is the total energy rotary wheel. All these devices are usually incorporated in ventilation or air-handling units (AHU) that take in outdoor air while venting indoor air. Exhaust air from the building interior passes through one side of the HR device while the incoming makeup air passes through the other side.

Total energy recovery devices transfer both sensible heat and moisture. During the cooling period the outdoor air is precooled and dehumidified. The transfer of heat and moisture is reversed during the heating season, namely the outdoor air is preheated and prehumidified by removing both sensible heat and moisture from the exhaust air stream and releasing it into the supply air stream. Sensible energy devices transfer only sensible heat and no moisture is recovered. The indoor air simply precools the incoming outdoor air during the cooling season while during the heating season heat is transferred from the warmer indoor air to preheat the incoming outdoor air. An analytical comparison of the characteristics, performance factors, advantages and use limitations of HR devices are given in [1, 2]. Mardiana-Idayu and Riffat [3] and Cuce and Riffat [4] present detailed reviews of HR systems and technologies for building applications.

Contemporary, well designed HVAC systems usually integrate one or more HR devices. Air-to-air, fixed-plate, cross-flow heat exchangers are the most common into processing the supply air, mostly because of their low cost and ease of installation. Cost and energy savings typically determine which type of HR device best suits a particular application. The potential benefits depend mainly on the ventilation airflow requirements, the climatic parameters, the effectiveness of the heating exchanger (HE), and the duration of the HVAC system's operation.

A series of studies has been conducted to determine the applicability and the benefits of HR systems, and their impact on the building's energy performance. Fehrm *et al.* [5] showed that HR is a necessity in northern and central European climatic conditions and concluded that primary energy consumption can be reduced by a minimum of 20% in Germany and Sweden. Besant and Simonson [6] calculated the energy recovered and the annual savings, by installing an air-to-air sensible HE in the HVAC system of a building. Lazzarin and Gasparella [7] evaluated HR ventilation (HRV) systems in three cities with different climates in Italy by taking into account the recovered energy, the reduction in heating and cooling capacity, and the operation time of the systems. They concluded that the payback period is related to the climate and to the HR system's characteristics.

Zhong and Kang [8] investigated the applicability of air-to-air HR systems in four different climates in China and showed that the selection of the type of HR system and its efficiency is strongly related to the climate. Other studies [9-11] focused on the significant impact of the climate conditions on the energy savings achieved by HR systems.

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The scope of this paper is to calculate (a) the heating and cooling energy that can be recovered, (b) the reduction in cooling and heating equipment capacity, and (c) the expected payback period from the installation of an air-to-air fixed-plate cross-flow heat exchanger in a HVAC system. The application is considered for four cities, representative of climatic zones A, B, C, D of Greece, which also represent typical Mediterranean climate conditions. A university auditorium is used as a model in order to calculate the expected energy and cost benefits from the installation of such a heat exchanger. The modified bin method [12] was used for the energy analysis and a spreadsheet program was constructed specially for this purpose. Energy calculations were performed both as with and without the HE, and with full or half occupancy. The energy consumption, the installation and the operating energy costs of the HVAC system were evaluated and compared, and the expected payback period was computed. The effects of the capacity and size of primary and secondary heating and cooling equipment were also examined.

Description of the conditioned space and HVAC system

The space under consideration is a 250-seat university auditorium, located at the ground floor of a 5 storey office building and is used mostly for classes and lectures from 9 a. m. to 9 p. m., during the working days of the week. The auditorium is conditioned by a single-duct, single-zone, constant volume, all-air HVAC system, which is the most appropriate for a single room of this size, with uniform load behavior and considerable ventilation air needs. The HVAC system consists of an AHU, the air duct distribution system, an electrically driven chiller, a gas boiler, a humidifier, the piping network, and the control system. The general layout of the system's component parts is shown in fig. 1.

The system provides heating, cooling, humidification and dehumidification during the whole year. The fresh ventilation air is drawn in the AHU through an intake diffuser and is mixed, if needed, in a mixing chamber with air

Figure 1. Layout of the HVAC system at the auditorium; *1 – supply fan, 2 – coils section with humidifier, 3 – mixing box, 4 – air-to-air heat exchanger section, 5 – return fan, 6 – bag filters, 7 – by-pass dampers*

returning from the conditioned space. The mixed air is filtered and then conditioned to the desired inside conditions. If the system is in the cooling mode, the air is cooled and dehumidified before entering the space, while in the heating mode it is heated and humidified, at a suitable temperature and moisture content. By installing an air-to-air heat exchanger in the AHU, the exhaust and the fresh outdoor airstreams are passing through the HE, before leaving/entering the mixing box respectively, as it is shown in fig. 1. In this case, the incoming outside air is precooled (during cooling season) or preheated (during heating season) by the exhaust airstream, achieving a reduction of the sensible portion of the ventilation air cooling and heating loads.

A gas boiler supplies hot water to the heating coil, a chiller supplies cold water to the cooling coil, and a steam humidifier discharges steam into the conditioned air. The supply air, after being properly processed in the AHU, it is transported through the supply fan and the
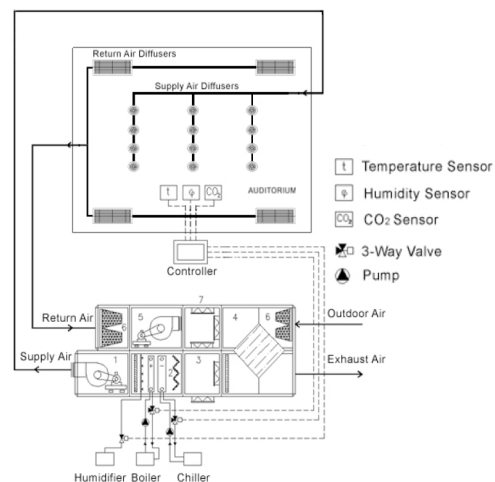
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supply air duct network, to the auditorium room. The return air is driven back to the AHU with the return fan, through the return air duct network. Since the space load varies as a function of time and occupancy, varying amounts of heating or cooling energy are needed to match the heating and cooling load.

The control system

The size and capacity of HVAC systems are typically calculated with design conditions. Nevertheless, full load conditions occur only during a rather small fraction of the operational hours whilst partial load/occupancy conditions are the rule. The control system regulates the operation of the HVAC system and enables its response according to changes in load and ventilation needs, so as to preserve a good indoor air quality and maintain thermal comfort conditions, with efficient plant operation and reduced energy use. The control system of the auditorium's HVAC plant is equipped with sensors for room air temperature, humidity and CO_2 concentration, connected to a central controller. The latter regulates the position of three-way valves, installed at the heating and cooling coils, the steam flow from the humidifier, and the position of the dampers at the mixing box. In this way, at part load/occupancy conditions, only the appropriate amounts of energy and ventilation air are supplied. Fresh outdoor, and consequently exhaust, airflow, are regulated according to occupancy. Under normal operation, these two airstreams pass through the air-to-air HE. In the cooling season, when the temperature of outdoor air falls between the exhaust air temperature and the indoor discharge air temperature, the system operates with the economizer cycle. The two airstreams – exhaust and outdoor – instead of crossing the HE they pass through the by-pass dampers of the mixing box. This function prevents the adding of heat to the outdoor fresh air, and accordingly to the cooling coil, and reduces the ventilation load and the running time of cooling equipment.

The HVAC system design criteria

The heating and cooling loads of the room were calculated according to the methods described in [13, 14]. Outdoor-indoor design parameters, namely dry-bulb (DB) temperature, wet-bulb (WB) temperature, relative humidity (RH) plus ventilation airflow requirements were adjusted according to national technical directives and codes [15, 16], and are given in tab.1. Climate conditions of zones A, B, C, D [17] correspond to the Greek cities Heraklion, Athens, Thessaloniki, and Florina, respectively. The climate in Greece is typical of the Mediterranean

Table 1. The HVAC system design criteria

	Climate zone			
	A	B	C	D
Number of people at full occupancy	250			
Outdoor air required [15]	8 L/s.person			
Room DB temperature (Summer/Winter) [15]	26 ºC/22 ºC			
Room RH (Summer/Winter) [15]	50/40%			
Outdoor DB/WB design conditions (Summer) [16]	32.5 ºC/23 ºC	35.5 ºC/22 ºC	35 ºC/23 ºC	33.5 ºC/21 ºC
Outdoor DB/WB design conditions (Winter) [16]	7 ºC/5 ºC	3 ºC/1 ºC	–2 ºC/–3 ºC	–7 ºC/–8 ºC

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climate, characterized for the most part by mild to cool wet winters and warm to hot dry summers. It varies from the hot/warm temperate dry of South and East Greece (zones A and B) to the cool/cold temperate wet climate of Northern and Western Greece (zones C and D). A great variety of climate subtypes, always within the Mediterranean climate frame, are encountered in several regions of Greece due to the influence of topography; the many hours of sunshine are their common feature. The vast majority of the country is classified Csa at the Koeppen scale, although some mountainous areas are Dwb or Dwf.

From the design heating and cooling loads results, it is concluded that the load for cooling and dehumidifying the outdoor air of ventilation is about the 50% of the total cooling load, with an exception in zone D where it represents 30% of the total load (due to low temperatures during some periods of the day during summer). The load for heating the outdoor ventilation air varies from 89% to 92% of the total heating load, for the four climate zones respectively. From these results it is presumed that there is a great potential for energy savings by applying HRV, especially during the heating season.

The supply air flow rate of the system Q_{su} [m^{-3}s] is calculated with the following equation:

$$Q_{su} = \frac{q_{sr}}{pc(t_r - t_{su})} \tag{1}$$

where q_{sr} [W] is the space sensible design cooling load, $\rho = 1.204$ kgm^{-3} – the density of standard dry air, $c = 10^3$ Jkg^{-1}K^{-1} – the specific heat of dry air, t_{su} [ºC] – the supply air temperature, and t_r [ºC] – the space DB temperature.

The required supply air flow rate, calculated according to eq. (1), is resulted in all four cities less than the required ventilation rate with full occupancy, which is equal to 7200 [m^{3}h^{-1}], thus the HVAC system operates with 100% outside air. During part load occupancy, a percentage of return air is recirculated at the mixing box of the AHU and is mixed with the outdoor fresh air.

When no air-to-air HE is installed in the AHU, the temperature of the ventilation air entering the mixing box is equal to the outdoor temperature. In the case of an air-to-air HE installation, with only sensible HR, the temperature of the outdoor ventilation air leaving the HE and entering the mixing box is calculated according to the definition equation of the HE sensible effectiveness:

$$\varepsilon_s = \frac{m_{su}(t_{suo} - t_{sui})}{m_{min}(t_{exi} - t_{sui})} = \frac{m_{ex}(t_{exi} - t_{exo})}{m_{min}(t_{exi} - t_{sui})} \tag{2}$$

where, ε_s is the sensible effectiveness of the air-to-air HE, m_{su} kgs^{-1} – the supply dry air mass flow rate, m_{ex} kgs^{-1} – the exhaust dry air mass flow rate, m_{min} kgs^{-1} – the smaller of m_{su} and m_{ex}, t_{sui} [ºC] – the supply moist air entering temperature, t_{suo} ºC – the supply moist air leaving temperature, t_{exi} ºC – the exhaust moist air entering temperature, t_{exo} ºC – the exhaust moist air leaving temperature. Equation (2) assumes state steady conditions; no heat transfer between the HE and its surroundings, and no condensation or frost formation on heat exchanger surfaces. In this project the effectiveness ε_s is taken equal to 0.50.

With the installation of the air-to-air heat exchanger in the AHU, the total cooling load decreases from 10% to 15% and the total heating load is reduced by about 39% for all zones, with a corresponding reduction in the required chiller and boiler capacity, and in the size and capacity of water pumps. However, the static pressure drop of the system increases; so do consequently the supply and return fan total pressure requirements. The magnitude of the pres-

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sure drop through the device and the configuration of the fans determine how much additional energy is consumed. The electrical input power of the supply and return fan is 1.2 and 0.65 kW without the air-to-air HE, while it increases to 1.1 and 1.7 kW, respectively, when the HE is installed. The extra pressure drop due to the HR device in the system is 200 Pa. The operating cost savings provided by recovered energy must exceed the increased cost of operating the fans in order to offset the cost of the HR device. A year-round energy analysis must be performed to determine the overall effect on the energy consumption of the HVAC system.

Energy analysis

The energy analysis was performed by applying the modified bin energy calculation method, which simulates the building loads and the operation of the primary and secondary equipment, and is therefore often used for the evaluation of HR systems [12]. Besides being easy to apply, it takes into account the frequency distribution of outside temperature and humidity, and hence the part load performance of the system and the variations of the chiller energy efficiency ratio and coefficient of performance during summer and winter operation. Bin weather data of the previously mentioned four Greek towns were taken from [18-20]. A spreadsheet program was developed and the energy requirements of the auditorium, along with the energy consumption of the HVAC equipment, were calculated for the following cases:
(a) Full occupancy – without air-to-air HR,
(b) Full occupancy – with air-to-air HR,
(c) Half occupancy – without air-to-air HR, and
(d) Half occupancy – with air-to-air HR.

Calculations were performed for every month of the year, for all those cases and all climate zones. For reasons of brevity, only the total annual results are presented in this paper. The electric energy consumption [kWh_{el}] of chiller, fans, pumps and humidifier along with the boiler's thermal energy consumption [kWh_{th}], during the cooling and heating period were calculated for each of the above mentioned four cases and are shown in tabs. 2-5. In the case of full occupancy (tabs. 2 and 3) the air-to-air HR HE saves about 40% of the total thermal energy required for the operation of the system, in all zones, fig. 1. Total annual electric energy consumption decreases by 1.7, 2.8, and 0.2%, for the zones A, B, C, respectively, and only in zone D it increases by 4.5%, fig. 2.

Table 2. Energy consumption results without air-to-air HE – full occupancy (250 persons)

Equipment energy consumption	Climate zone							
	A	B	C	D	A	B	C	D
	Cooling period				Heating period			
Chiller [MWh_{el}]	17.57	14.86	13.70	5.03				
Boiler [kWh_{th}]					30.42	49.17	64.76	90.81
Supply fan [MWh_{el}]	2.10	2.13	2.12	2.06	1.40	2.01	2.36	2.68
Return fan [MWh_{el}]	1.26	1.28	1.27	1.24	0.84	1.24	1.40	1.61
Water pumps [MWh_{el}]	0.24	0.24	0.24	0.23	0.07	0.10	0.11	0.13
Humidifier [MWh_{el}]					1.28	2.36	5.85	12.81
Total electric energy [MWh_{el}]	21.17	18.51	17.33	8.56	3.59	5.71	9.72	17.23
Total thermal energy [MWh_{th}]					30.42	49.17	64.76	90.81

The chiller's electrical energy consumption is reduced in all zones by 2.2%-12%, depending on the zone, but the installation of the HE increases the pressure drop in the AHU and leads to a 16% increase of the energy consumption by the fans. In zones A, B and C this increase is offset by the decrease in chiller's energy demand but in zone D the reduction of chiller energy consumption is less than the increase of energy consumed by the fans.

When the system operates without the HE, the chiller consumes 71%, 61%, 51%, and 20% of the total electric energy, while the fans and pumps 24%, 29%, 28%, and 31%, in zone A, B, C and D, respectively. The rest is consumed by the humidifier. When an air-to-air HE is installed the chiller consumes 66%, 55%, 46%, and 18% of the total electric energy on annual basis, while the fans and pumps 28%, 35%, 32% and 34%, in zone A, B, C and D, respectively.

In the case of half occupancy (tabs. 4 and 5) the HR device reduces the total thermal energy about 31%, in all zones (fig. 1). The total annual electric energy consumption is increased in all zones, and more specifically by 1.4, 0.7, 2.2, and 6.7%, for the zones A, B, C and D respectively. The chiller's electric energy consumption remains the same in zone D and decreases by 4.4%-6.9%, in zones A, B, and C (fig. 2).

Table 3. Energy consumption results with air-to-air HE - full occupancy (250 persons)

Equipment energy consumption	Climate zone							
	A	B	C	D	A	B	C	D
	Cooling period				Heating period			
Chiller [MWh$_{el}$]	16.22	13.07	12.46	4.92				
Boiler [kWh$_{th}$]					18.31	29.39	38.44	53.40
Supply fan [MWh$_{el}$]	2.38	2.41	2.40	2.34	1.59	2.34	2.65	3.03
Return fan [MWh$_{el}$]	1.54	1.56	1.55	1.51	1.03	1.51	1.71	1.96
Water pumps [MWh$_{el}$]	0.24	0.24	0.24	0.23	0.07	0.10	0.11	0.13
Humidifier [MWh$_{el}$]					1.28	2.36	5.85	12.81
Total electric energy [MWh$_{el}$]	20.38	17.28	16.65	9.00	3.97	6.31	10.32	17.93
Total thermal energy [MWh$_{th}$]					18.31	29.39	38.44	53.40

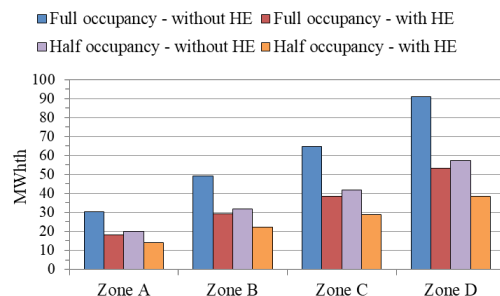**Table 4. Energy consumption results without air-to-air HE – half occupancy (125 persons)**

Equipment energy consumption	Climate zone							
	A	B	C	D	A	B	C	D
	Cooling period				Heating period			
Chiller [MWh$_{el}$]	14.63	14.14	12.20	4.48				
Boiler [kWh$_{th}$]					20.00	31.97	41.86	57.23
Supply fan [MWh$_{el}$]	2.10	2.13	2.12	2.06	1.40	2.06	2.34	2.68
Return fan [MWh$_{el}$]	1.26	1.28	1.27	1.24	0.84	1.24	1.40	1.61
Water pumps [MWh$_{el}$]	0.24	0.24	0.24	0.23	0.07	0.10	0.11	0.13
Humidifier [MWh$_{el}$]					0.64	1.18	2.93	6.39
Total electric energy [MWh$_{el}$]	18.23	17.79	15.83	8.01	2.95	4.58	6.77	10.81
Total thermal energy [MWh$_{th}$]					20.00	31.97	41.86	57.23

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Table 5. Energy consumption results with air-to-air HE – half occupancy (125 persons)

Equipment energy consumption	Climate zone							
	A	B	C	D	A	B	C	D
	Cooling period				Heating period			
Chiller [MWh$_{el}$]	13.98	13.17	11.5	4.51				
Boiler [kWh$_{th}$]					13.98	22.12	28.75	38.60
Supply fan [MWh$_{el}$]	2.38	2.41	2.40	2.34	1.59	2.34	2.65	3.03
Return fan [MWh$_{el}$]	1.54	1.56	1.55	1.51	1.03	1.51	1.71	1.96
Water pumps [MWh$_{el}$]	0.24	0.24	0.24	0.23	0.07	0.10	0.11	0.13
Humidifier [MWh$_{el}$]					0.64	1.18	2.93	6.39
Total electric energy [MWh$_{el}$]	18.14	17.38	15.69	8.59	3.33	5.13	7.40	11.51
Total thermal energy [MWh$_{th}$]					13.98	22.12	28.75	38.60

As in the case of full occupancy, the installation of the HE increases the energy consumption of the fans by 16%. Nevertheless, in half occupancy, the decrease in chiller's energy demand is less than the increase of energy consumed by the fans, resulting in the increase of the total electric energy consumption. Without the heating energy, the chiller consumes 69%, 63%, 54%, and 24% of the total electrical energy, while the fans and pumps 28%, 31%, 33%, and 42%, in zone A, B, C, and D, respectively. The rest is consumed by the humidifier. When an air-to-air HE is installed the chiller consumes 65%, 58%, 50% and 22% of the total electric energy on annual basis, while the fans and pumps 32%, 36%, 37% and 46%, in zone A, B, C and D respectively.

Therefore, both in the case of full and half occupancy, the installation of the air-to-air HE reduces significantly the total thermal energy consumption (fig. 3). The electrical energy consumption for cooling is generally decreased, with a gradual reduction from cold to warm climate zones. The electric energy consumption for humidifying, on the contrary, progressively increases from dry and warm (A and B) to wet and cold zones (C and D). The installation of the HR HE reduces the energy consumption for heating, cooling, humidifying and dehumidifying, but electrical energy for fans is raised. This increase affects the total electrical energy consumption of the system. An economic analysis is therefore required to evaluate if the installation of the HE is beneficial.
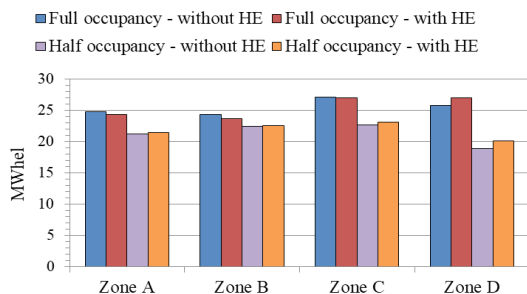
Figure 2. Annual electric energy consumption of the HVAC system

Figure 3. Annual thermal energy consumption of the HVAC system

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The HVAC system design criteria

The reductions in energy use are linked to annual cost savings using actual energy cost data: electricity costs 0.19 €/kWh and natural gas 0.070 €/kWh, which is average value of natural gas in Athens and Thessaloniki (all rates at end 2016). Although the cities of Heraklion and Florina have no gas network, for reasons of comparison it is assumed that the boilers are gas fired.

With these rates, the total annual energy cost is shown in tab. 6. In the case of full occupancy, the installation of the HE reduces the yearly total energy cost by 13.6, 18.8, 19.2, and 21.3%, for the climate zones A, B, C, and D, respectively. In the case of half occupancy the yearly total energy cost is reduced by 6.8, 10.2, 11.0, and 14.0%, for climate zones A, B, C, and D. These cost reductions are mainly a consequence of the significant decrease in thermal energy operating cost. Namely, although in some cases the electric energy cost increases, the installation of the HE is always beneficial for the final total operating cost. If oil use is assumed instead of natural gas, the cost reduction is even greater due to the higher price of oil (~0.1 €/kWh) and the higher percentage of thermal energy in the total energy recovery. Energy savings and cost reduction must offset the cost of the HR device. The use of air-to-air HR usually permits a smaller heating and cooling plant, but it may lead to increase in the fans' motor size. In this project, the investment cost of HVAC system in the four cities, was determined according to price lists of HVAC equipment dealers and installers in the Greek market. The design configuration with HR proved to be more expensive than the typical system with no recovery in zones B, C, and D, while in zone A, no extra investment is needed. With the use of payback method the payback period was calculated.

Table 6. Annual operating cost [€] and total cost savings [%]

Occupancy	Full (250 persons)				Half (125 persons)			
Climate zone	A	B	C	D	A	B	C	D
Energy cost [€] – without air-to-air HE								
Electric energy (cooling)	4,021	3,518	3,292	1,627	3,462	3,381	3,007	1,523
Electric energy (heating)	682	1,093	1,842	3,271	560	868	1,258	2,052
Thermal energy (heating)	2,129	3,442	4,534	6,357	1,401	2,238	2,930	4,006
Energy cost [€] – with air-to-air HE								
Electric energy (cooling)	3,871	3,284	3,165	1,710	3,446	3,304	2,983	1,632
Electric energy (heating)	753	1,198	1,960	3,387	631	973	1,405	2,188
Thermal energy (heating)	1,282	2,058	2,691	3,758	978	1,548	2,013	2,702
Total Cost savings	926	1,514	1,852	2,400	368	662	795	1,059
Savings [%]	13.6	18.8	19.2	21.3	6.8	10.2	11.0	14.0

The results indicate that with full occupancy the expected payback period is less than 1 year for all climate zones (1, 7, 4, and 10 months for climate zones A, B, C, and D). Even with half occupancy, the maximum payback period is less than 2 years (1, 17, 9, and 23 months for climate zones A, B, C and D). These results refer to a continuous operation of the HVAC system from 9 a. m. to 9 p. m. and during all working days (Monday to Friday). With occupancies between 50% and 100%, the expected payback period is in all cases between 1 and 24 months,

according to climate zone and occupancy rate. Also, when oil is used in zone D the payback period further decreases. There are also the uncertainties of future energy prices, which may prolong or shorten this period. In a recent research [21] it was concluded that the payback period of a sensible recovery HE, in 24-hour operating ventilation systems, is less than 4 months in Mediterranean countries. Any increase in electricity price by 10% reduces the cost savings rate by 5% in the case of full occupancy and by about 8% in the case of half occupancy. Nevertheless, the total cost savings and the expected payback period are not considerably affected. If a HE with higher effectiveness ε_s is chosen, the increased effectiveness must be valuated against the increased initial cost.

Conclusions

The research discussed on this paper covers the energy and economic analysis of an air-conditioning system for a university auditorium that utilizes sensible HR, in various Mediterranean climate conditions. Four Greek cities were selected, representing the four climate zones of Greece which correspond well to cities in Mediterranean countries like Cyprus, Croatia, Italy and France: two of them have hot/warm temperate dry climate, and the other two cool/cold temperate wet climate conditions. As it was proven, the installation of an air-to-air sensible heat exchanger is a cost-effective way of pre-conditioning outside ventilation air, for all climatic conditions and both for full and half occupancy patterns. The annual total energy cost is reduced by 6.8 to 21.3% according to occupancy and climate zone, with a progressive rate from warm to cold climate conditions mostly due to the significant reduction of the thermal energy cost, while the energy cost for cooling is not notably reduced. The payback period of the extra investment for the HR device does not exceed 24 months, depending on climate zone and on whether the system operates at full, intermediate or half occupancy.

The findings discussed in this paper on the one hand confirm the results of previous studies and on the other underline the necessity to thoroughly consider the impact of the HR systems with respect to partial load conditions and varying energy prices. In that sense, further investigation is needed in order to examine if the installation of other types of energy recovery devices is beneficial, and on how the feasibility is influenced, when the HVAC systems operate with less than 100% outside air and for varying hours during the day. It is a research that is worth carrying out, because HVAC systems of this type and size are common and widespread. They can be found from universities' auditoria to cinema halls and from events' halls in hotels to restaurants and bars. It is therefore clear, that they present a well suited and feasible case for the application of waste HR technologies, as part of an energy renovation strategy to improve the efficiency of existing buildings, while moving towards the Nearly Zero Energy Building.

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