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Feasibility study of a heat recovery system in an office building in Malta

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Abstract. The new Energy Performance of Buildings Directive (EU) 2018/844 has brought about a new drive to renovate existing buildings, especially for heating and cooling systems, whereby heat recovery techniques have become the order of the day. However, the real energy and financial benefits of applying such techniques have not been studied in Malta, which has a temperate Mediterranean climate. Thus, this study has performed a technical and financial analysis of using different heat recovery options for the most common office type, that is a medium-sized flatted office, using EnergyPlus dynamic simulation tool and multiple linear regressions. Results showed that the coefficient of performance of the air-conditioners, the window to wall ratio and the cooling set-point temperatures, have the greatest impact, while heat recovery has an insignificant contribution to energy efficiency, thus making it rank low in the list of energy efficiency priority measures for medium-sized offices in Malta.

Keywords: heat recovery, ventilation, office buildings, Malta, energy efficiency

1. Introduction

The use of heat recovery units coupled with mechanically ventilated air-conditioning systems are becoming increasingly popular in offices, as they are believed to save energy from space heating and cooling by pre-heating or pre-cooling the incoming fresh air. Suppliers of such systems usually quote high energy saving figures and short payback periods, based on the respective manufacturers' brochures. The common practice hypothesis is that sensible and latent heat recovery devices are economically feasible for office buildings and that they take priority in renovation and new projects. Locally, there is little awareness that the brochures are based on specific testing conditions and are often quoted for central European (predominantly space heating demand) climate. In Malta, the climatic conditions are Mediterranean, hence the temperature difference between indoors and outdoors is not as large as in continental Europe. Moreover, most offices in Malta operate during the day when the weather is by large mild to warm and humid. The current minimum energy performance requirements as set by Technical Document F [1,2] , is not committal on this aspect. Given Malta's 2020 targets for energy efficiency [3], this study helps policymakers to understand the energy savings potential for introducing such practices and devices. This study will focus on one typical office building where a parametric analysis has been performed for different office operation scenarios, equipment specifications and envelope constructions, while the building's geometry remains fixed. A sensitivity analysis was carried out to identify the parameters that have the biggest impact on the technical and economic feasibility of heat recovery devices. Currently, there is no available literature or publications on heat recovery devices for mechanical ventilation systems in the context of the Maltese climate and use in buildings. This highlights the importance of this study.

The study therefore intends to analyse:

- The impact on energy consumption when energy recovery devices are introduced in space heating and cooling systems;
- The impact on the energy savings potential and economic feasibility using different input parameters by parametric analysis;
- The financial feasibility of heat/energy recovery devices versus the base scenario of mechanical ventilation without heat/energy recovery.
- The correlations between energy and cost saving for the use of heat/energy recovery systems in office buildings having different operational (including comfort requirements), envelope and equipment specifications.

2. Literature review

2.1. Energy performance of buildings: EU directives and national legislation

Energy consumption has increased drastically in the past few years [4] with Malta being the top EU Member State in 2017 with increased energy demand. The EU has launched several directives such as the Energy Performance of Buildings Directive (EPBD) 2010/31/EU [5], (EU) 2018/844 [6], and the Energy Efficiency Directive 2012/27/EU [3], in order to try to achieve nearly zero-energy buildings [7]. Malta has also set its targets in order to abide by the new EU legislations, as stated in Malta's 2020 targets [3, 4, 5]. In fact as of January 2021, all new buildings must be Nearly Zero-Energy Building (NZEB) [8]. The Building Regulation Office (BRO) also emphasize the importance of heat recovery ventilation system in Technical Document F [2] whenever it is 'economically feasible'. However, the latter term is not well defined. This leaves the choice in the hands of the designer on a case by case basis, which does not contribute towards a holistic approach, which reflects the lack of studies performed on this type of technology for the Maltese climate. Passive ventilation measures help to reduce energy demand but quite often such measures are not enough to ensure adequate supply of fresh air in offices [10, 11]. Therefore, the introduction of mechanical ventilation systems would ensure indoor air quality, while at the same time a heat recovery unit saves energy from air-conditioning [9]. Mechanical ventilation along with space conditioning will inevitably increase running costs of a building, sometimes even up to 50% of the total running costs of a large building [10]. Therefore, it is important to harmonize the mechanical ventilation system to minimize electrical consumption, while keeping acceptable levels of indoor air quality.

2.2. Modelling energy recovery systems

In dynamic simulation, the use of specialised modelling software is crucial since it calculates all criteria as based on the location of the test subject. This method is crucial to acquire exact results of the operating conditions and the expected benefits [11]. Dynamic simulation is favoured according to the European Standard EN ISO 13790:2018 [12] in order to improve the quasi-steady state method, since this works with dynamic parameters that reduce the thermal gains for heating [13]. One dynamic simulation software that can be used for buildings is EnergyPlus [14].

2.3 Case studies employing air to air heat recovery

Energy saving potential of energy recovery devices depend grossly on the climate conditions and indoor temperature set-points [15, 16, 17, 18, 19], since energy recovery increases with increasing temperature difference between inside and outside [20, 21]. Previous studies showed that the Mediterranean climate (Csa) is the only one where space heating and cooling energy consumption increased when an ERV system without bypass was implemented [17, 22, 23] and that an ERV might improve the relative humidity and energy efficiency depending on the climate [17]. The energy savings of an ERV depends on the enthalpy recovery medium, the coefficient of performance (COP) of the air-conditioning, outdoor climate conditions, enthalpy efficiency, fan power consumption and fresh air changing rate [24]. Energy saving is dependent on the operating periods and it is influenced by the type of heat exchanger the building utilizes. In general, a total (sensible and latent) heat exchanger type achieves more savings [25], compared to a sensible heat exchange one [19].

2.4 Gaps in literature
A review of the literature showed that no studies have been performed to understand the energy savings potential for mechanically ventilated office buildings equipped with air to air heat or energy recovery, operating in the Maltese climate.

3. Methodology
DesignBuilder [26] software which runs on Energyplus engine [27] was chosen to simulate the mid-floor flatted office building. Parameters such as the weather file for the selected site, the construction materials of the building envelope, the zone operations and schedules, the set temperatures for systems such as HVAC, lighting, as well as the technologies of these services were all defined and inputted in the software.

3.1. The building envelope
The office building has the following dimensions: 24 m by 6 m and 3.5 m ceiling height. Two walls, the floor and ceiling were assumed to be adjacent to interior zones and were set as adiabatic. Windows were applied on the remaining two exposed walls as seen in Figure 1. The sizes of these windows will be later varied in size to gauge their effect on the performance of the heat recovery system.

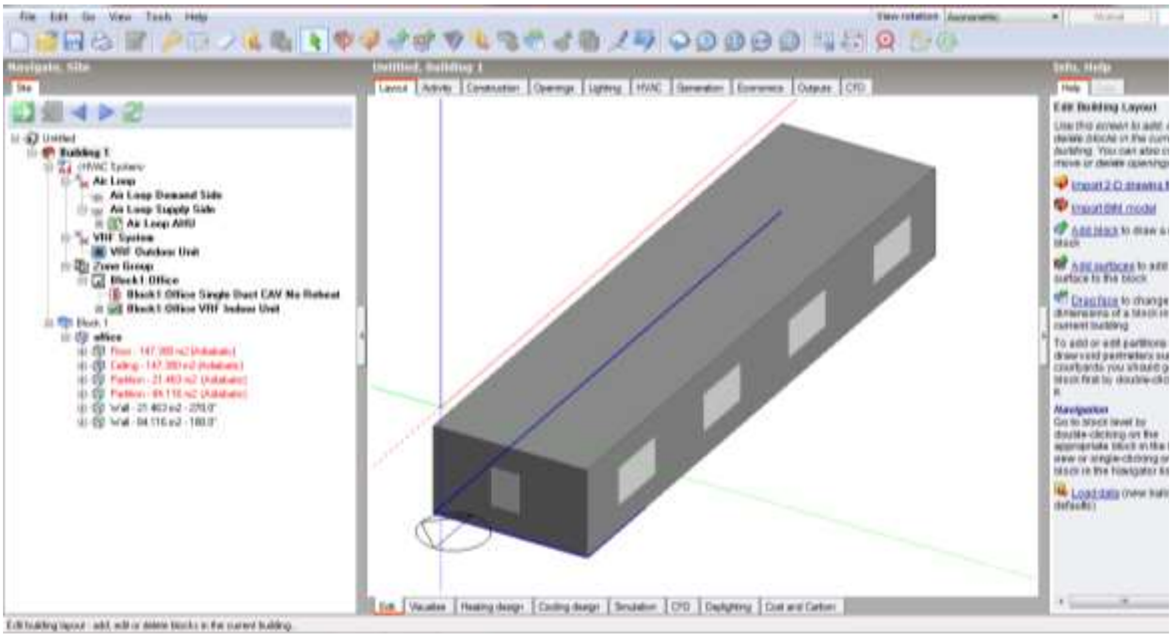

Figure 1. Geometry of the office building depicted in DesignBuilder software

3.2. Building office set parameter
Malta's meteorological weather file for the year 2010, which is applied for the national energy performance certification for non-dwellings SBEM-mt software [28], was used. The power density of the office equipment was set to 11.77 W/m^2, occupancy level to 0.111 people/m^2 and metabolic rate to 123 W/person. The office hours were set as follows: 0% at 7:00 hrs, increases to 100% at 12:00pm and decreases to 25% at 19:00 hrs. Weekends and holidays are unoccupied. The thermal comfort set points were set as 24^{o}C for cooling and 22^{o}C for heating. Office light luminance was set to 400 lux and LED light bulbs with a power density of 2.5 W/m^2 per 100 lux were used. Fresh air ventilation of 10 l/s per

person was applied. The office building wall construction was set with a U-value of 1.52 W/m^2K with internal heat capacity of 149.56 kJ/m^2K. The openings for this office building were set to be made of aluminum windows having a frame thickness of 0.04m, window to wall ratio of 20% as a base scenario, window aluminum frame U-value of 5.88 W/m^2K and window frame heat capacity of 6.16 kJ/m^2K. The window glass was set to have a total of 0.7 solar transmission, 0.78 light transmittance and U-value of 3.09 W/m^2K.

3.3. Office HVAC equipment

The Variable Refrigerant Flow (VRF) heat recovery, dedicated outdoor air system (DOAS) found in the DesignBuilder template list was used for the study. The VRF was set to have a cooling and heating COP of 4.8 and 5.8, respectively. The plate heat exchanger was selected. The sensible and latent heating and cooling efficiencies were set as follows, 0.75 at 75% air flow and 0.70 at 100% airflow. The mechanical DOAS ventilation system was designed to have on/off fixed speed control and is automatically sized to meet the design load air change requirements of 10 lires/s/person. The economizer option was not considered in this study.

3.4. Heat recovery bypass

The energy management system (EMS) in Energyplus [27] was used to manipulate the sensors and an actuator was introduced to provide control for the DOAS ventilation system. The logic of this program enabled the automatic bypass of the heat recovery when outside temperatures are beneficial.

3.5. Simulation studies on the office building

The building energy model with no heat recovery and no bypass was set as the base scenario. Annual simulations with an hourly data resolution were performed to compare the base scenario with the following:

a) Scenario 1: DOAS incorporating sensible heat recovery with no bypass
b) Scenario 2: DOAS incorporating latent heat recovery with no bypass
c) Scenario 3: DOAS incorporating sensible heat recovery with bypass (EMS activated)
d) Scenario 4: DOAS incorporating latent heat recovery with bypass (EMS activated)

3.5.1. Sensitivity Analysis.

A Global Sensitivity Analysis (GSA) for all the above scenarios including the base scenario was performed to statistically determine which parameters have the biggest impact on the space heating and cooling requirements of the office building.

The following parameters were defined probabilistically using uniform distributions with the ranges shown in brackets: Window to wall ratio (20 to 80%), Cooling set point (22 ºC to 26 ºC), heating set point (20 ºC to 24 ºC), occupancy density (0.11 to 0.15 people/m^2), mechanical ventilation rate per person (7 to 12 litres/s/person), site orientation (0° to 315º), HVAC system efficiency (COP values varied between 2.8 to 4.8 in cooling and 3.8 to 5.8 in heating). These parameters were found from the literature to potentially influence the technical and economic feasibility of air to air heat recovery systems. The ranges for the probability distributions for comfort and equipment parameters were based on the requirements of EN 15251 standard [29] and eco-directive regulations.

For the GSA, Latin Hypercube Sampling (LHS)[1] was used to automatically draw a combination of samples from the parameter distributions and automatically perform over 1,600 simulations.

[1] Latin Hypercube Sampling "*attempts to generate a sparser set of samples than design of experiments using pseudo-random distributions of independent variables*" [30].

4. Results and discussion

4.1. Annual and monthly energy performance analysis

From Table 1, when using the parameters shown in section 3.1 to 3.4, it can be observed, that the space heating energy of the office building is minimal due to internal heat gains of people, equipment and solar gains, are enough to achieve the set-point temperature. Due to this low space heating energy demand, only 18.97 kWh (electric) per year of savings is achievable corresponding to 10 % of the total space heating demand for all scenarios. During January, February, March and December outside temperatures are lower than the set-point temperature, thus providing a potential for sensible heat energy recovery. This makes the by-pass system redundant for these months.

When the building is in cooling mode the electrical energy savings compared to the base scenario, ranges between (-) 35 kWh per annum (2 % increase) in the case of no-bypass (scenario 1) to 69 kWh per annum (3.8 % reduction), in the case of the bypass valve. This shows that on an annual basis the heat recovery with no bypass is not desirable. In addition, for space cooling, one can observe that both latent energy recovery and a bypass system have a role to play in providing a better energy performance. This is because of the observed latent cooling loads (refer to Figure 2) and the requirement to bypass the heat recovery for the shoulder months.

Table 1. Annual simulation results

	Annual results							
	Sensible Cooling energy demand	Total Cooling energy demand	Total Heating energy demand	Heat recovery hourly potential	% heat recovery potential	VRF total cooling electrical energy	VRF total heating electrical energy	VRF electrical energy savings
	kWh	*kWh*	*kWh*	*Hrs*	*%*	*kWh*	*kWh*	*kWh*
Base scenario - No heat recovery	8858.86	10168.76	100.33	-	-	1824.91	18.97	-
Scenario 1 - Sensible no bypass	9380.48	-	12.20	884	18.60	1859.28	1.89	1.76
Scenario 2 - Total no bypass	9415.85	10491.79	12.20	939	19.70	1820.45	1.89	20.6
Scenario 3 - Sensible bypass	8751.11	-	12.20	1096	23.10	1787.98	1.89	59.14
Scenario 4 - Total bypass	8784.05	9870.21	12.21	1234	26.00	1755.42	1.89	91.39

Furthermore, when considering the overall energy performance, the potential energy savings when compared to the base scenario ranges between 1.76 kWh (0.1 % improvement in energy performance) for scenario 1 and 91.3 kWh (5 % improvement in energy performance) for scenario 4.

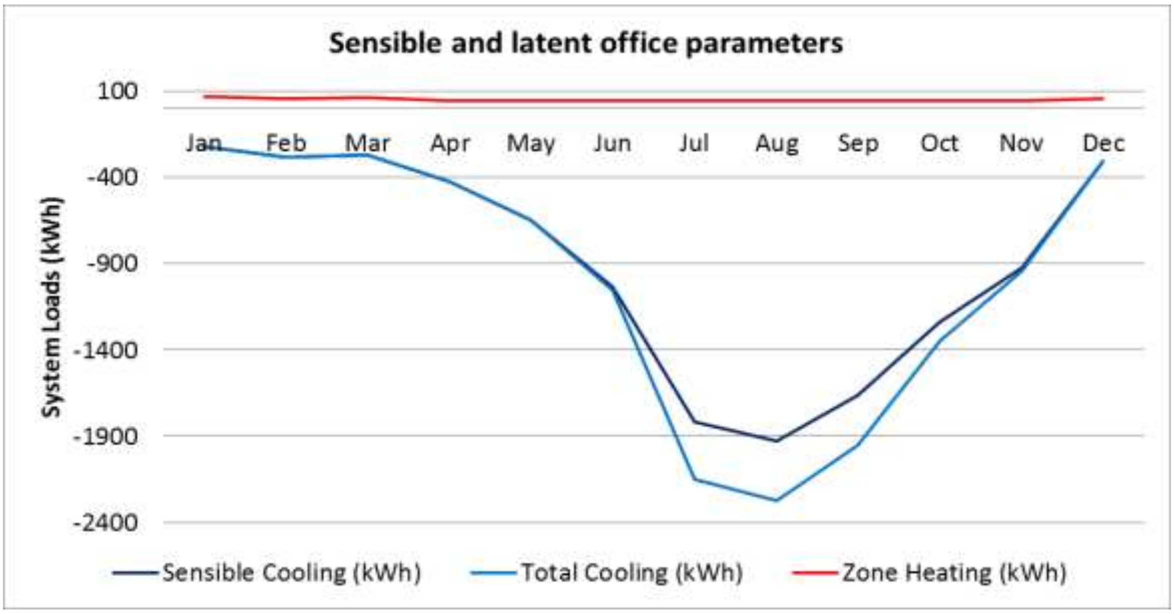

Figure 2. Sensible and latent monthly loads

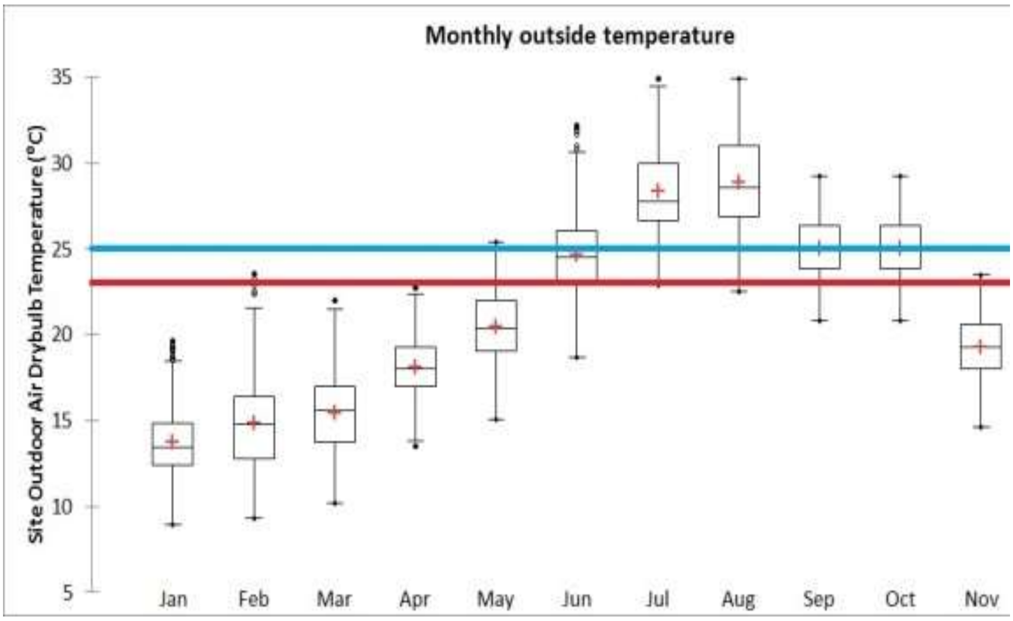

Figure 3. Monthly temperature values

Monthly data results show that the bypass system is mainly required for the months of April, May, September and October, where the system is in cooling mode. In Figure 3, one can also observe that in April and May most of the hourly outside temperatures lie below the 25 °C set-point temperature and so bypass is beneficial to provide free cooling. Adding a heat recovery device during these months will heat the incoming air, leading to an increase in the cooling load for the building. For the months of September and October, there are also a total of 109 hours (10 hours in September and 99 hours in October), for which the building can operate in free-cooling mode.

Figure 4 and Figure 5 show that in November, the same energy performance is achieved both for the base scenarios and the scenarios with heat recovery, because of a minimal outside and inside temperature difference during working hours and given that internal heat gains contribute to reaching the desired comfort temperature. It is important to note that the air-conditioning system is only set to operate during the working hours and not during the night.

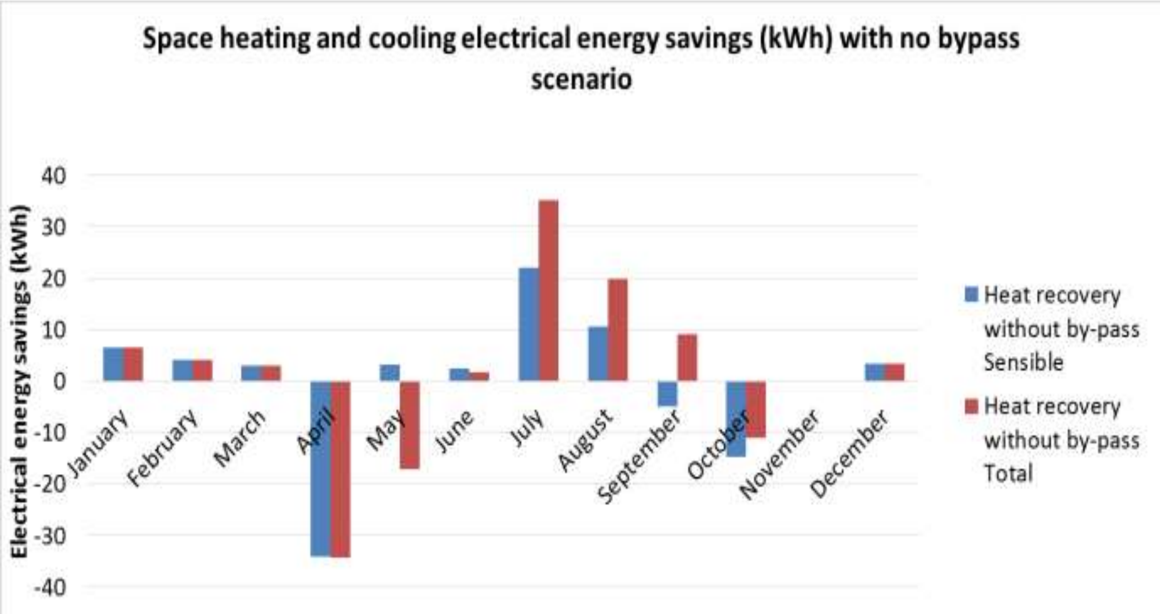

Figure 4. Monthly energy savings for sensible and total heat recovery system with no bypass

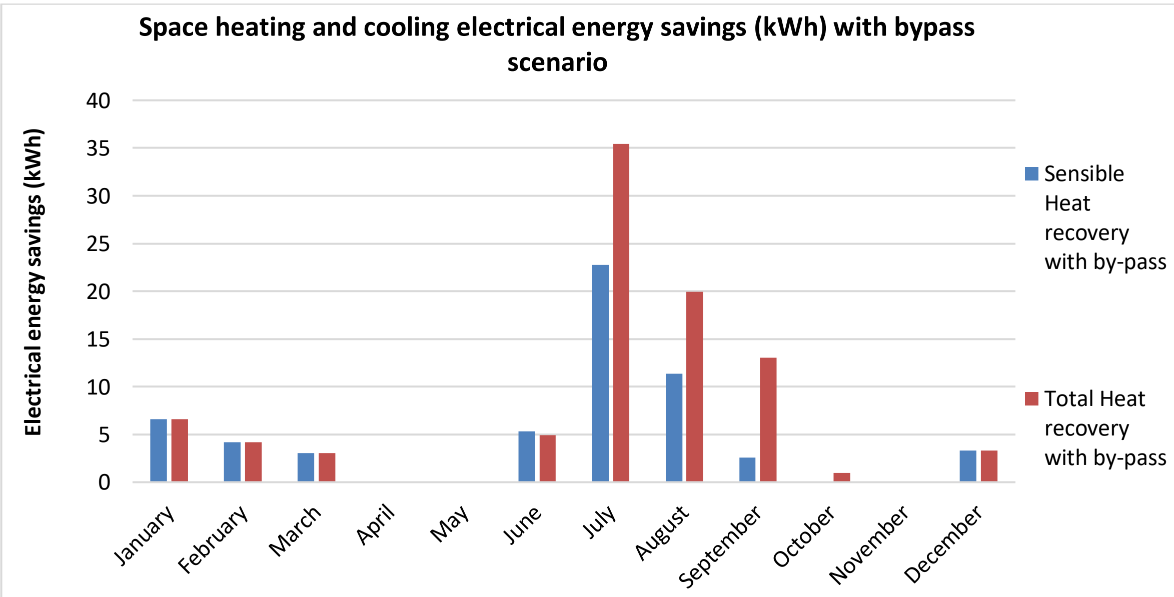

Figure 5. Monthly energy saving for sensible and total heat recovery system with bypass

Following on these results, a simplified mode of bypass control for the office building can be the elimination of heat recovery during the shoulder months and November.

The energy savings between May and November are greater for total energy recovery space cooling than for sensible only, as can be seen in the graphs of Figure 6 and Figure 7. The reason for this is that during these months there are latent cooling loads in addition to sensible cooling loads, which can both be recovered, as shown in Figure 2.

When considering the peak loads of the system, all scenarios present a similar decrease in the electrical peak load compared to the base scenario with no heat recovery. During the summer design week, 370 W peak electrical power reduction is achievable when introducing a heat recovery system and in winter, a potential of 74 W peak electrical power reduction is possible. If one considers this for all Malta's office buildings a substantial reduction in peak electric power can be achieved.

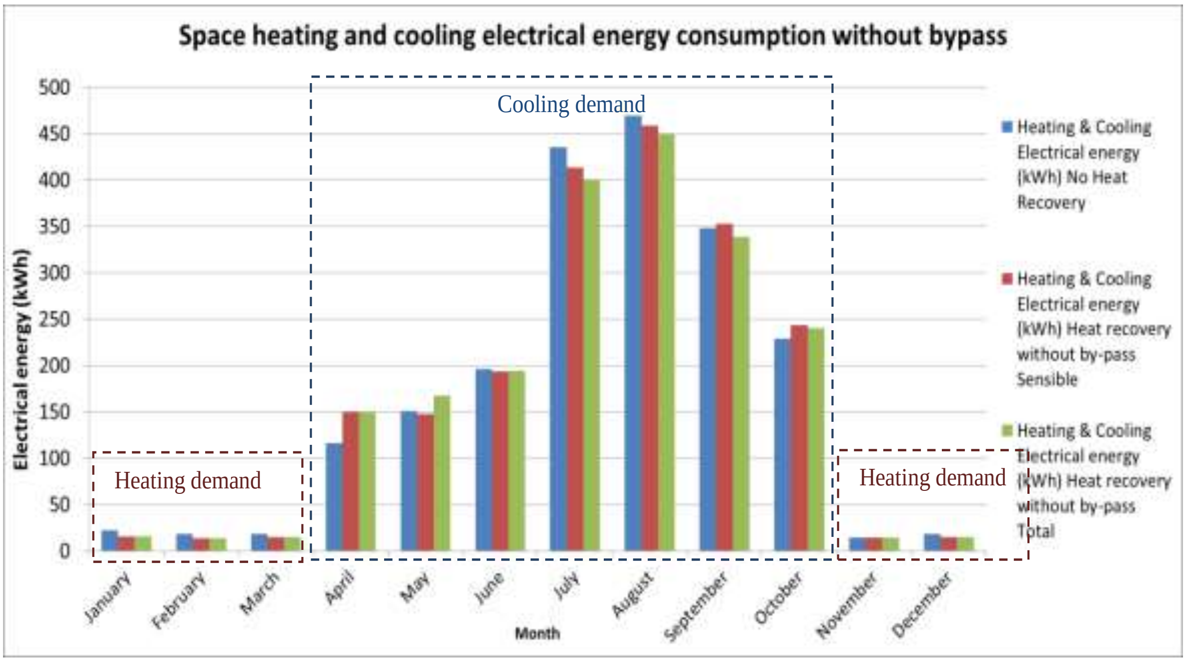

Figure 6. Monthly Electrical energy consumption without a bypass system

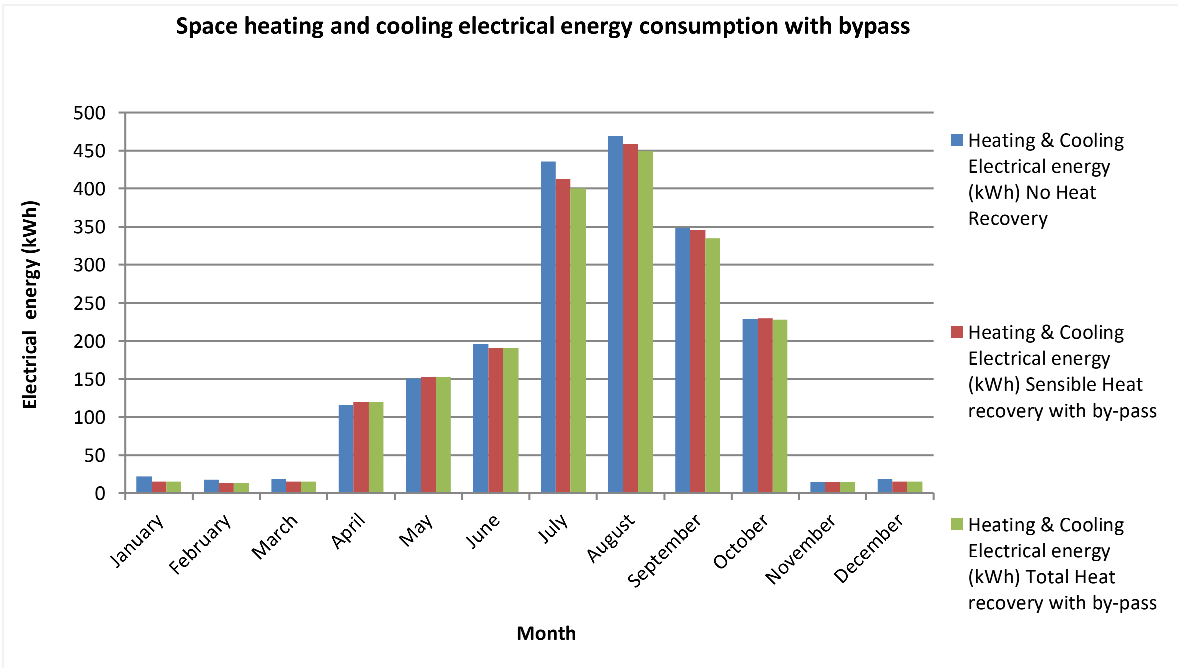

Figure 7. Monthly Electrical energy consumption with a bypass system

Heat recovery savings, from a private investor's perspective, resulted to be not feasible given that the lowest payback periods were beyond the lifetime of the system for the total heat recovery system with bypass. This analysis was done based on a €3,400 capital cost for a heat recovery, €510 bypass system and a € 0.1275/kWh electrical tariff rate, assuming that there is no increase in the energy consumption from the mechanical ventilation fan system, to overcome the pressure drop caused by the heat recovery.

4.2. Parameterisation and Global Sensitivity Analysis

From the GSA using Multiple Linear Regression (MLR), for different orientations results, it is shown from Table 2 and Table 3, that heating temperature set point, mechanical ventilation rate and heat recovery do not statistically have a significant impact (p-value >0.05) on annual space heating and cooling.

The tables also show via the resulting standard regression coefficients that the factors having the biggest impact on electrical space heating and cooling energy performance are HVAC efficiency, cooling temperature set point and the window to wall ratio. Heat recovery only has a relative impact of 6%, when compared to HVAC efficiency. Thus, priority should be given to these parameters, as these have the highest impact on the space heating and cooling energy demand of the building, as can be seen in Table 2 and Table 3. When analysing the impact of the bypass system, it was found to be statistically not significant (p-value >0.05).

Table 2. MLR analysis with no bypass

Testing for linear model simulations with no Bypass			
Equation	**R^2**	**Standardized Coefficients (β)**	
y = 11766.106 + 41.439 (WWR%) - 402.777 (Cooling temp) + 28.298 (Heating temp) + 4224.970 (Occ density) + 16.939 (Mech vent) + 1.255 (Orientation) - 1134.183 (HVAC eff) - 68.501 (HR)	0.836	WWR%	0.55
		Cooling Temp.	-0.36
		Heating Temp	0.03
		Occ. density	0.04
		Mech. vent	0.02
		Orient.	0.09
		HVAC eff	-0.62
		HR	-0.04

Table 3. MLR analysis with bypass

Testing for linear model simulations with Bypass			
Equation	**R^2**	**Standardized Coefficients (β)**	
y = 12179.669 + 41.553 (WWR%) - 400.798 (Cooling temp) + 16.685 (Heating temp) + 3572.983 (Occ density) + 1.237 (Orientation) - 1121.399 (HVAC eff) - 83.981 (HR)	0.832	WWR%	0.55
		Cooling Temp	-0.36
		Heating Temp	0.02
		Occ. density	0.03
		Orient	0.09
		HVAC eff	-0.61
		HR	-0.04

From these results of the Global SA, one can observe that heat recovery system should not be considered as a priority for reducing the space heating and cooling energy requirements for such office buildings, unless a financial support scheme is set to encourage their use, given their positive effect on reducing peak power demand on the power station in summer. In a standard medium-sized office, the priority for energy efficiency should focus on carefully managing the comfort temperature set-points, optimising the WWR in terms of unprotected glazing and optimising orientation prior to considering air to air heat recovery for ventilation. Thus, policymakers should carefully consider the results of global SA when identifying measures to be promoted to improve the energy performance of such office buildings.

5. Conclusion

This paper studied the effectiveness of introducing heat recovery systems for medium sized flatted offices in Malta. It is concluded that:

- Maximum potential electrical energy savings for heat recovery resulted to be only 91.39 kWh/year (or 5 % of the total space heating and cooling electrical energy demand) when total energy recovery with bypass was implemented. Furthermore, the resulting simple payback period when considering these savings was found to greatly exceed the equipment lifetime.
- July and August provided the maximum savings for heat recovery. Furthermore, during the shoulder months (April, May and October), heat recovery is not favorable as it increases the energy consumption for space cooling given that the direct supply of outside air temperature has the potential for free cooling during these months.
- The bypass system for total heat recovery was found to reduce the electrical energy consumption for space heating and cooling by a 3.6 % when compared to the total heat recovery system without bypass.
- Total energy recovery versus sensible recovery was found to provide maximum improved electrical energy savings of only 30 kWh/year. Total energy recovery versus sensible heat recovery provided an improved energy performance only during the cooling season with maximum potential recorded during the months of July and August, given the high latent cooling loads inside the building during those months.
- While heat recovery was shown to provide only minimal energy savings for such office buildings, it was found to have a greater potential in reducing the peak power demand in summer and winter. During the summer period a reduction of 370 W in peak electrical power was achievable, which is a substantial reduction when considering total office building stock.
- From the results of a parameterisation and global sensitivity study, it was found that the impact of heat recovery (using standardised beta coefficients) on combined electrical annual space heating and cooling of the office buildings is 15 times less than the impact of heat pump efficiency, 13.75 less than the impact of the window to wall ratio, and 9 times less than the impact of the cooling set-point temperature. Thus, to improve the energy performance in a building, one should prioritise energy efficient equipment space heating and cooling, optimally manage the temperature set-points and optimise the Window to wall ratio prior to the consideration of air to air heat recovery system for ventilation.

Given the minimal achieved energy savings and the resulting large pay-back period, the implementation of heat recovery devices should no longer remain an automatic choice for implementation in medium-sized office buildings in Malta. Policy makers or equipment suppliers should not rely on the energy savings of heat recovery devices stipulated in technical brochures of foreign (cold) climates. In such climates, heat recovery may have a much higher positive impact given the larger temperature difference between the incoming fresh air and the set indoor comfort temperature. It is therefore recommended that prior to making any investment decisions, heat recovery is carefully evaluated against other energy efficiency alternatives, while taking Malta's central Mediterranean climate fully into consideration.

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