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Analysis of the impact of different HVAC configurations and control strategies on primary energy and cost savings for an office building

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Abstract

In order to mitigate climate change, sustainable and responsible use of resources is required. In the present study, different technologies applicable for the renovation of an office building are evaluated considering, both economic feasibility and environmental impact for the climates of Rome Stuttgart and Stockholm. Decentralized heating and cooling systems represented by different types of heat pumps (i.e. air-to-air On/Off and modulating) are considered in combination with photovoltaic panels (PV), battery and efficient lighting (LED) in order to investigate the achievable energy savings and the additional cost. The environmental impact is evaluated in terms of electricity and total primary energy (PE) savings calculated with constant and monthly conversion factors representing different scenarios with different share of renewables in the electricity mix. It was observed that the energy savings calculation method influences the ranking of renovation packages. High-energy savings with low additional cost are achievable with HP in combination or not with LED and PV, in Stockholm and Stuttgart, and with LED and PV in combination with electric heating in Rome. Battery brings additional energy savings with high additional cost.

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1. Introduction

In spite of higher efficiency, the energy consumption of buildings has increased over the past decades and the European Union has set restrictive targets. To reach these goals, buildings have to be transformed from energy consumer to energy provider. In non-residential buildings, the available façade area for the installation of a renewables based system is limited and an optimization of the building system is required in order to reduce the primary energy demand.

The recast of the Energy Performance of Buildings Directive [1] states that member state (MS) must ensure that minimum energy performance requirements for buildings are set “with a view to achieve cost-optimal levels” in terms of global cost and primary energy need. The cost-optimal level must be calculated in accordance with a comparative methodology.

In the literature, some studies dealing with both economic feasibility and environmental impact for office buildings are present but they do not consider different scenarios for the evaluation of the influence of the electricity mix. Pikas E. et al. [2] is focused on the building envelope considering different fenestration design solutions. Gustafsson M. et al. [3] investigated energy renovation packages involving centralized heating and cooling system, windows, envelope insulation and solar photovoltaics (PV), for European office buildings. Sanja Stevanović presented a cost optimality study [4] for an office building located in Serbia where the cooling demands is predominant.

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Ochs F, et al. [5] introduces a PE evaluation method considering different future development of the load (i.e. building stock) and electricity mix (share of REs) with seasonal variations. This works highlight the need of an appropriate evaluation method for comparing and ranking different passive and active technologies on micro- and macro- economic scale. Different EU MS adopts different national conversion factors for PE/CO₂, which are subject to change [5]. Seasonal variations are not considered at all, although the share of renewables within the period of consideration (e.g. 20 years) should be included [5].

In this work different HVAC retrofit solutions (i.e. HP, PV, Batteries, LED etc..) are compared against a reference case involving an electric heating system with an On/Off split unit for cooling and fluorescent lamps combining both economic and environmental analysis. A sensitivity analysis is carried out in order to evaluate the influence of input parameter (i.e. interest rate, investment cost and electricity price) on the results of the economic analysis. The environmental analysis is performed using different share of renewables in the electricity mix showing the impact of the development of increasingly share of RE on the ranking of the different retrofit solutions.

2. Method

2.1. Building model and boundary conditions

The reference building is chosen in order to be representative of a typical European office cell located in middle floor of a high-rise building [6]. Three different European climates are considered in this study: Rome (Mediterranean), Stuttgart (cold moderate) and Stockholm (cold climate). Fig. 1 shows the considered office cell, which has a heated area of 27 m² and a volume of 81 m³. All the surfaces are considered adiabatic, except for the façade oriented toward South (with window-to-wall ratio of 60%) where ambient boundary conditions are applied. Shading from adjacent obstacles is not considered, whereas an external movable shading, able to block 70% of the incoming radiation, is activated when direct solar radiation impinging the south façade is higher than 120 W/m².

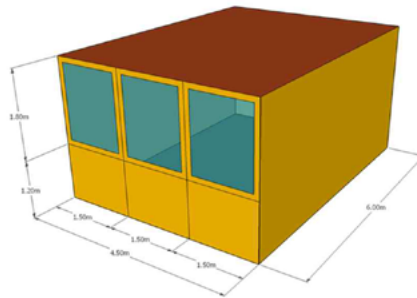


Fig. 1. View of the reference office zone [6]

Table 1 shows the yearly average ambient temperature ($T_{amb,av}$), yearly global irradiation over a horizontal surface ($I_{g,h}$) and yearly irradiation over a south oriented vertical surface (I_{south}) for each climate.

The thermal transmittance of the façade elements ($U_{ext,wall}$) and the characteristics of the windows such as the thermal transmittance (U_{win}), the solar heat gain coefficient (g-value) and the solar transmittance (τ_{sol}) depend on the three climates, as shown in Table 1. The internal walls are typical plasterboard walls, the exterior wall is a three layer structure with different insulation thicknesses depending on the climate.

User behavior (e.g. occupancy, appliances and lighting) is taken into account by means of hourly profiles, different for week and weekend days [7]. A contemporaneity index of 0.8 is used for occupancy and appliances. Three persons are present during the working time and a sensible and latent heat of 70 W/person and 0.08 kg/h/person are considered. The internal gain due to appliances is assumed to be 7 W/m² and the electric gain due to lighting is 10.9 W/m². The lighting schedule follows occupied hours and is defined considering a non-daylight responsive system

The natural infiltration rate is assumed to be constant and equal to 0.15 l/h. A fresh air supply of 40 m³/h/person is covered by a mechanical ventilation system with heat recovery (70% sensible efficiency), which is active only during the working time (i.e. from Monday to Friday from 8:00 am until 08:00 pm).

Table 1. Main properties of the south oriented façade and climates [6]

	$T_{amb,av}$ [°C]	$I_{g,h}$ [kWh/m ²]	I_{south} [kWh/m ²]	$U_{ext,wall}$ [W/m ² K]	U_{win} [W/m ² K]	g-value [-]	τ_{sol} [-]
Rome	15.8	1632	1253	0.80	1.26	0.33	0.462
Stuttgart	9.9	1101	889	0.40	1.35	0.59	0.426
Stockholm	7.8	952	884	0.20	0.90	0.63	0.260

An anti-freezing resistance is heating up the ambient air when the external temperature falls below 0°C while a bypass of the heat recovery is activated when the temperature of the zone is higher than 23 °C and the ambient temperature is lower than the indoor temperature. The set point temperature for the indoor convective temperature during the wintertime and summertime are 21°C and 25°C. A detailed description of the boundary conditions is reported in D'Antoni, et al. [6]. The building model is developed in Matlab/Simulink and it has been validated against other dynamic simulation tools [8].

2.2. Renovation packages

The renovation packages discussed in this paper include the combination of different heating, cooling and lighting technologies optionally combined with PV and battery without modifying to the envelope. In addition, the effect of different control strategies is considered.

Table 2 reports all the technologies involved in this study highlighting in bold the reference system used for the comparison (i.e. electric heating and On/Off HP for cooling with a standby consumption running for the entire year, fluorescent lighting and the reference control system for the ventilation and free-cooling described in section 2.1). The electric heating system can be retrofitted with either a simple On/Off or improved modulating HP that might cover also the cooling load.

In the reference case the free cooling can be activated only during the working time therefore savings in terms of cooling demand can be achieved when the free cooling is activated every time the internal and external conditions makes it effective.

Switching off completely the cooling system during the winter season, enable savings by reducing the standby consumption. Switching off the heating and cooling systems during non-occupied periods (night set-back) might enable further savings. Moreover, using modern LED instead of fluorescent lamps can approximately halve the electricity consumption for lighting purpose.

Table 2. Characterization of the investigated renovation components

	Options	Description
Heating	Direct electric	Electric resistance, efficiency equal to 1.
	On/Off (Split type) HP	See Fig. 2. Two different On/Off HP sizes are considered.
	Modulating (Split type) HP	See Fig. 2.
Cooling	On/Off (Split type) Air-Con.	See Fig. 2. Two different On/Off HP sizes are considered.
	Modulating (Split type) Air-Con.	See Fig. 2.
PV	Mono-crystalline silicon	PV installed in the available wall area (5.4 m ²) in the south façade with an efficiency of 17.7% and a peak power of 877 Wp.
Battery	Ideal battery	Efficiency of 90% (4kWh capacity).
	HP and mechanical ventilation	On/Off HP and PI for the modulating HP, for the mechanical ventilation see the building description.
Control	Free cooling 7/7	Free cooling can be activated every time the internal and external conditions makes it effective.
	Improved standby consumption	Standby consumption of 10W accounted only during the working season of the considered technology (instead of the whole year).
	Night set back	The heating and cooling systems are switched off during non-occupied periods and restarted 4h before the working time.
Lighting	Fluorescent	10.9 W/m ² (500 lux on the working desk, 8 luminaire).
	LED	5.45 W/m ² (500 lux on the working desk, 8 luminaire).

As specified in Table 2, two On/Off HP with different sizes and one modulating HP are considered in this work. The main characteristics (i.e. COP, EER, heating and cooling power and air volume flows) are reported in Table 3 and the maps of performances in Fig. 2.

Table 3. Main characteristics of the modulating and On/Off heat pumps. The heating power and COP are specified for the external air temperature of 15°C and internal of 22°C while the cooling power and EER are specified for the external air temperature of 35°C and internal of 27°C. For the modulating HP the performances are specified for the maximum f_{max} and minimum f_{min} frequency.

	Internal air volume flow [m³/h]	External air volume flow [m³/h]	Heating power (15°C/22°C) [W]	Cooling power (35°C/27°C) [W]	COP (15°C/22°C) [-]	EER (35°C/27°C) [-]
Modulating HP	648	1872	f_{max} : 4006 f_{min} : 1006	f_{max} : 2510 f_{min} : 1248	f_{max} : 5.44 f_{min} : 5.86	f_{max} : 5.29 f_{min} : 5.05
On/Off HP low power	187	1872	523	1250	4.12	4.28
On/Off HP high power	648	1872	3923	2510	5.38	5.29

Fig. 2 shows the performances of the modulating, On/Off low (lp) and high (hp) power heat pumps in cooling and heating operation used in the simulations. The COP of the On/Off HP (Fig. 2.2b) considers a degradation of the performance due to deicing when the ambient temperature is between 7°C and 2°C. The modulating HP is modelled with a separated deicing model therefore the COP reported in Fig. 2.1b does not consider the losses due to deicing operation.

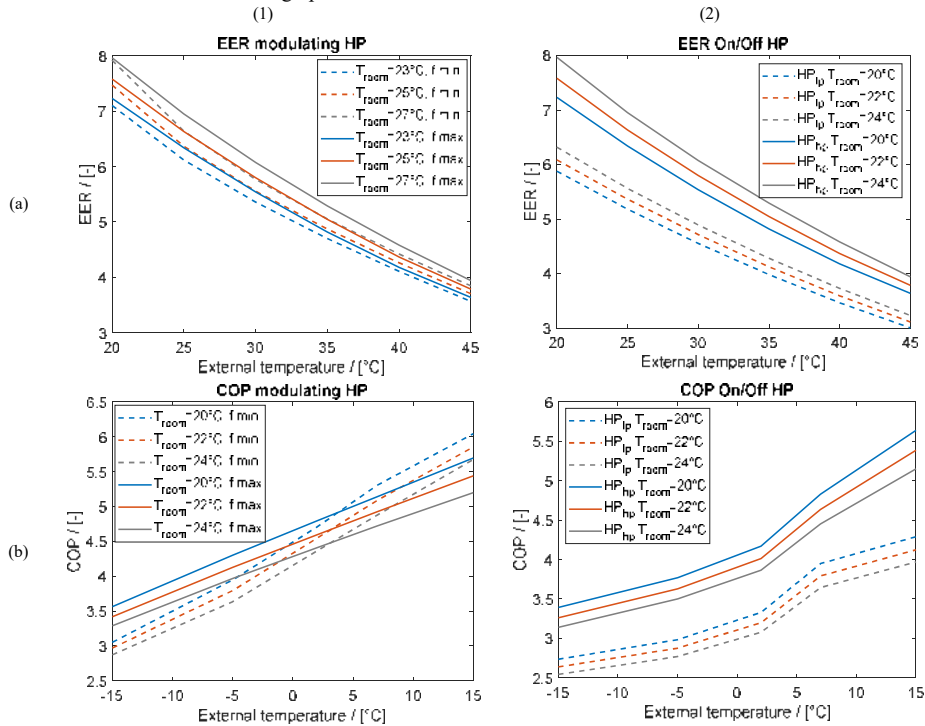


Fig. 2. Maps of performances of the modulating (1) and low power (lp) and high power (hp) On/Off (2) heat pump in cooling (a) and heating (b) mode

The schemes of the control system used for the On/Off and modulating HP are reported respectively in Fig. 3a and Fig. 3b. The On/Off HP is controlled with an hysteresis (± 0.5 K) having as input the temperature difference between the heating set point and the air temperature ($T_{set,H} - T_{air}$) during the heating mode and the temperature difference between the air temperature and the cooling set point ($T_{air} - T_{set,C}$) during the cooling mode. The Look-up-Tables (LuT) deliver as output the COP/EER, the absorbed electric power (P_{el}) and the delivered thermal power (\dot{Q}_{th}). The transfer function (TF) with a time constant of 130 s is necessary to slow down the

system response and makes the heat pump behaviour more realistic. The LuT have as input the control signal, the air temperature (T_{air}) and the ambient temperature (T_{amb}).

The modulating HP is controlled with a proportional integral (PI) control having as input $T_{set,H}-T_{air}$ during the heating mode and $T_{air}-T_{set,C}$ during the cooling mode. The equation (1) shows the PI control rule where the proportional parameter K_p is equal to 1 and the integral time constant T_n is equal to 418.7 s.

$$f(t) = K_p \cdot \left(err(t) + \frac{1}{T_n} \cdot \int err(t) dt \right) \quad (1)$$

The control system of the modulating HP includes also a minimum run (t_{ON}) and off (t_{OFF}) time and the deicing (t_{deic}). The deicing cycle, which last 600 s, starts only when the time counter reaches the defined waiting time that is a function of the ambient temperature (i.e. 11460 s for an ambient temperature of -7°C and 2406 s for an ambient temperature of 5°C). During the deicing cycle, the HP absorbs electric energy without delivering any thermal energy to the room. When the HP is switched on and is not performing the deicing cycle, it is forced to remain in operation with a frequency between the minimum and the maximum until the minimum run time counter reaches the threshold of 300 s. In the same way, when the HP is switched off, it is forced to remain in this status until when the minimum off time counter reaches the threshold of 600 s.

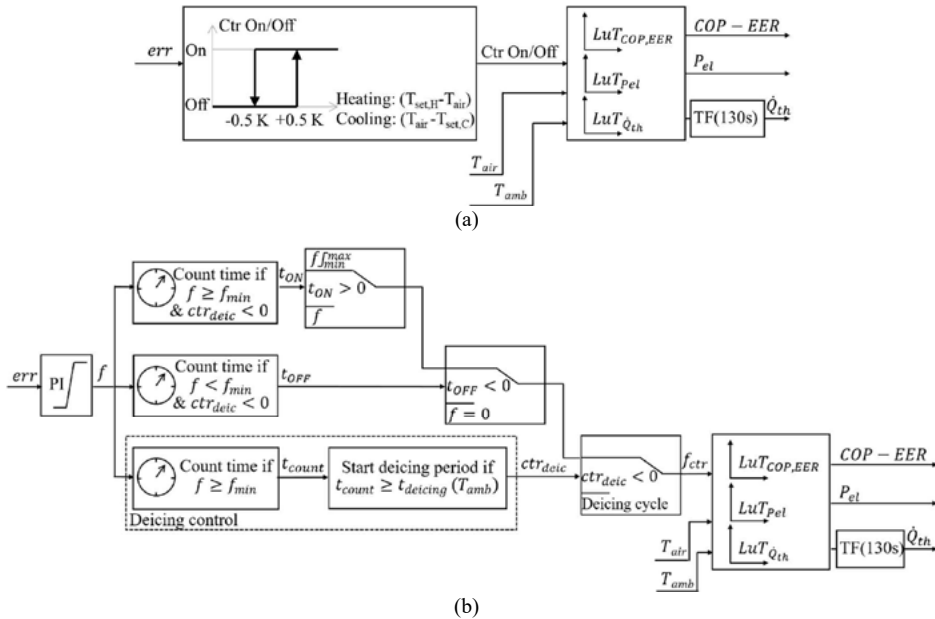


Fig. 3. Control of (a) On/Off and (b) modulating HP

The PV model from the Matlab/Simulink CARNOT library [9] is based on equation (2) and (3).

$$\text{Power}_{PV} = \left((25 - T_{m\ odub}) \cdot \Delta W_{p,T} + 1 \right) \cdot W_p \cdot f_{gen} \cdot \frac{Q_{sohr}}{1000} \quad (2)$$

$$T_{m\ odub} = \frac{Q_{sohr}}{1000 \left(\frac{W}{m^2} \right)} \cdot 40 + T_{amb} [^\circ\text{C}] \quad (3)$$

Where:

- $\Delta W_{p,T} = 0.00375$ is the temperature coefficient [1/K];
- $W_p = 877$ W is the peak power [W];
- $f_{gen} = 1 - 0.03$ is the efficiency of the PV considering losses in diodes, power mismatch and dirt;
- Q_{sohr} is the solar irradiation impinging the PV panel corrected with the Incidence Angle Modifier (IAM).

The model of the inverter is provided by the CARNOT library [9]. It considers a standby consumption of 1 W and the efficiency is a function of the output power (i.e. when the output power is between 300 W and 3600 W the efficiency is above 0.95).

2.3. Economic analysis

The economic analysis adopted in this work is based on the Equivalent Annual Cost (EAC), considering investment and running costs over a reference lifetime (N). EAC is the annual cost of owning, operating, and maintaining an asset over its entire life, it allows comparing the cost-effectiveness of various assets that have unequal lifespans. Equation (4) shows the calculation of the EAC:

$$EAC = \frac{C \cdot r}{1 - (1+r)^{-N}} \tag{4}$$

Where r is the real interest rate (3%). The total annual cost is calculated, for electrically driven systems, as:

$$Total\ annual\ cost = EAC + MC + FE \cdot el_{price} \tag{5}$$

Where MC is the yearly maintenance cost, FE is the final electric energy and el_{price} is the electricity price that is assumed to be 0.2 €/kWh. An escalation rate of the energy price of 2% is considered. A sensitivity analysis is carried out varying the interest rate, the investment cost and the electricity price in order to assess the sensitivity of the economic results to the input data. The annual interest rate is varied ±1% point from the default value (3%), the electricity price and the investment costs are varied ±20%. In Table 4 the investment, installation, maintenance costs, the technical lifetime and the resulting EAC for each technology are reported. The data for HP and PV are all taken from [3] except the investment cost of PV which is taken from [10] where mono-crystalline silicon PV are considered.

The reference technology for the cooling is the On/Off low power HP therefore when the modulating HP or the On/Off high power HP are considered, as a cooling technology, only the additional costs are accounted for (ΔEAC=143.5€).

The data for battery and LED are assumed considering the current price of different sellers. The battery are usually guaranteed for 10 years while LED for 50000 hours that correspond to a lifetime of 15 years.

The PV self-consumption contributes to the reduction of the electricity demand of the building system. When the battery is considered, the PV surplus energy is stored and later used by the building, otherwise the benefit of selling the surplus to the main grid is disregarded.

Table 4. Investment costs, installation costs, maintenance costs and EAC of the studied renovation measures

Renovation measure	Investment costs [€]	Installation costs [€]	Maintenance costs [€/y]	Technical lifetime [y]	EAC [€]
On/Off HP low power	500 [3]	100 [3]	16 [3]	12 [3]	76.3
On/Off HP high power	1400 [3]	290 [3]	50 [3]	12 [3]	219.8
Modulating HP	1400 [3]	290 [3]	50 [3]	12 [3]	219.8
PV (877 Wp)	2322 [10]	380 [3]	34.2 [3]	20 [3]	215.8
Battery (4.8 kWh) with Inverter	4000	1400	0	10	663.1
LED light (8 luminaire)	640	300	0	15	78.7

2.4. Environmental analysis

In this case study all the analyzed solutions are using electricity as input, therefore they can be compared considering the savings in terms of electricity demand. In order to compare the savings in terms of primary energy there is the need to define the proper conversion factors.

The increasing share of renewables in the electricity mix affects the definition of the PE/CO₂ conversion factors especially because the energy production from renewables is not constant during the year but rather has a seasonal trend. Significantly increased share of RE electricity can be expected in the near future in particular in summer, while in winter only a moderate increase is likely, unless there is a significant further extension of wind power or seasonal storage capacities are strongly build up [5].

For this reasons, different scenarios for the PE conversion factor are taken into account.

Fig. 4 shows the monthly PE conversion factors considering a constant coefficient defined in [11], a simplified

scenario with an energy mix of 10% hydro, 10% wind and 10% PV and an energy mix of 10% hydro, 30% wind and 30% PV. The difference between the EU conversion factor and the 10-10-10 or 10-30-30 scenarios is higher during the summer than during winter. This means that using the EU conversion factor the same value is given to savings obtained in summer and winter while using the monthly conversion factors (i.e. 10-10-10 and 10-30-30) less importance is given to the energy savings occurring in summer.

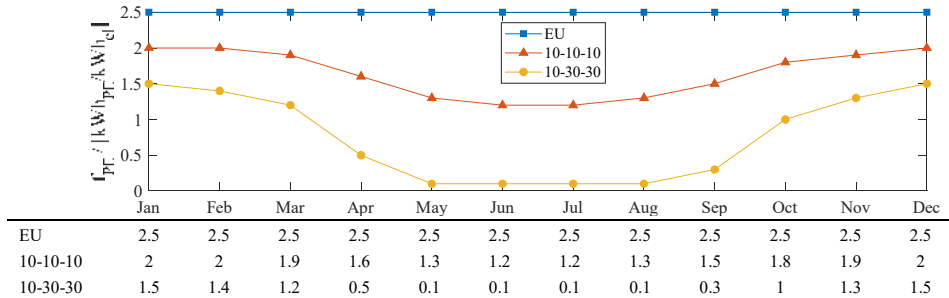


Fig. 4. Monthly total PE conversion factor defined according to (EU) European definition, (10-10-10) scenario where a share of 10 % hydro, 10 % wind, 10 % PV and 70 % fossil is considered in the electricity mix, and (10-30-30) scenario where a share of 10 % hydro, 30 % wind, 30 % PV and 30 % fossil is considered in the electricity mix [5]

3. Results

3.1. Reference case and PV yield

The reference case is composed of a direct electric heating system and an On/Off HP_{ip} without PV. Fig. 5a shows, for each climate, the monthly electricity demand per square meter of floor area (27 m²) for each component of the balance (i.e. heating, cooling, appliances, lighting, anti-freezing resistance of the heat exchanger and fans of the mechanical ventilation). The PV production in each climate is reported by the straight blue line. The cross (EU conversion factor), triangle (10-10-10 scenario) and square (10-30-30 scenario) markers refer to the right vertical axes reporting the primary energy consumption. As highlighted in section 2.4, increasing the renewables share in the grid leads to a reduction of the primary energy demand especially during the summer time.

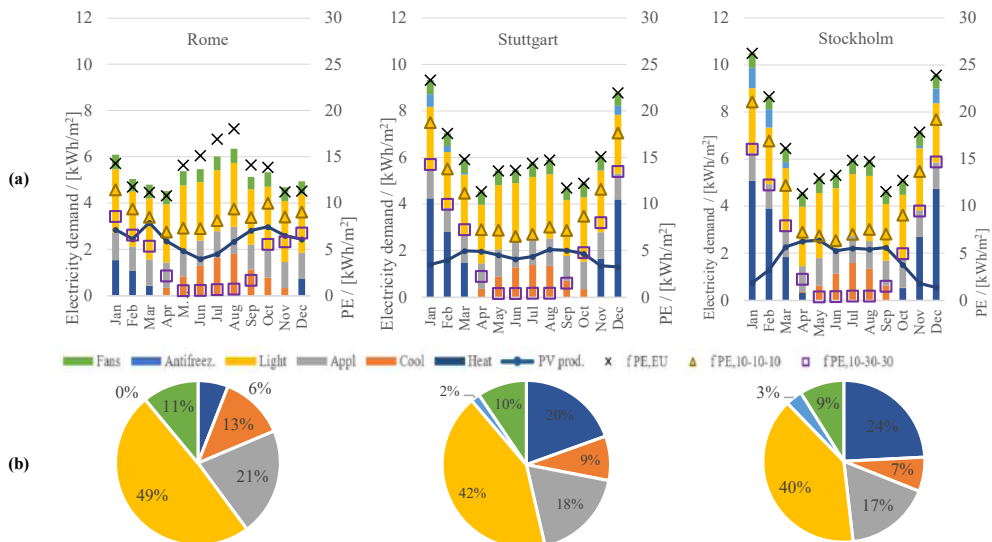


Fig. 5. Results for the reference case (direct electric heating and split HP) for the climates of Rome, Stuttgart and Stockholm. (a) Electricity demand for each end use and PV production; (b) share of electricity required by each end use.

Fig. 5b shows the share of electricity required by each end use, highlighting that the lighting is prevailing in each climate.

Table 5 reports the annual electricity consumption required by each end use and PV production for the climates of Rome, Stuttgart and Stockholm. The total electricity consumption of the reference case is 64 kWh/(m²y) in Rome, 74 kWh/(m²y) in Stuttgart, and 79 kWh/(m²y) in Stockholm. The PV total production would cover the 46%, 28% and 26% of the total consumption in Rome Stuttgart and Stockholm respectively. From this analysis is already clear that the installation of PV in the façade (BIPV) in this case study would bring important energy savings.

Table 5. Annual electricity consumption required by each end use and PV production.

	Heating	Cooling	Appliances	Lighting [kWh/(m ² y)]	Antifreez.	Fans	PV
Rome	4	8	14	31	0	7	29
Stuttgart	14	6	14	31	1	7	21
Stockholm	19	5	14	31	3	7	21

3.2. Pareto solutions

The results of the dynamic simulations investigating different HVAC and lighting solutions (see section 2.2) are compared to the base case considering the additional capitalized cost and energy savings. The latter are expressed in terms of electric energy (E_{EL}) and of total PE calculated with the constant conversion factor (PE_{EU}), with the 10-10-10 scenario ($PE_{10-10-10}$) and with the 10-30-30 scenario ($PE_{10-30-30}$).

Fig. 6 shows the energy savings in terms of (A) E_{EL} , (B) PE_{EU} , (C) $PE_{10-10-10}$ and (D) $PE_{10-30-30}$ versus the additional total annual cost (see Equation (5)) of each technology for the climate of Stockholm. Fig. 7 shows the energy savings in terms of (E, F) E_{EL} and (G, H) $PE_{10-30-30}$ versus the additional cost for the climate of Rome and Stuttgart, respectively. In both Fig. 6 and Fig. 7, the square markers represent the results of the different technologies together with the PV panels, while the asterisk markers represent the solutions including battery and PV. The error bars shows the results of the economic sensitivity analysis, indicating the impact on the additional total annual cost by varying the investment cost, energy price and interest rate. The investment cost has the highest impact on the economic evaluation.

In this specific case, the analysis of the results does not change considering the PE_{EU} or E_{EL} since all the compared solutions are using electricity as energy source (see Fig. 6 A and B).

The two objects of this optimization are the minimization of the cost and the maximization of the energy savings under the constraint of maintaining thermal comfort. In such a case, typically a feasible solution that minimizes all objective functions simultaneously does not exist. The optimal cases lay on the Pareto front composed by solutions that cannot be improved in any of the objectives without degrading the second object. In Fig. 6 and Fig. 7, the Pareto front, for the set of solutions considered in this work, is highlighted with a light green underlay. The red underlay highlights solutions that are not optimal since enable lower savings and same cost of at least one solution of the Pareto front. The differences in terms of energy savings between the On/Off low or high power and modulating HP are not significant in all the considered climates but the modulating HP and high power On/Off HP are more expansive than the On/Off low power HP.

The night set back slightly reduces the heating demand, therefore it has a small effect in Stockholm and Stuttgart but no effect in Rome where the heating demand is almost zero.

Switching off the air conditioner, when not in operation, i.e. the during the winter season for the case when the electric heating is active), reduces the standby consumption and comes without any additional costs.

The free-cooling active seven days per week on the one hand reduces the cooling demand while on the other hand increases the energy consumption of the fans, increasing also the overall energy consumption. When the $PE_{10-30-30}$ instead of E_{EL} is considered, the results of the cases with free cooling (see violet and dark green markers) are overlapped to the respective cases without free cooling (see yellow and light blue markers).

Since in the reference case almost half of the electricity demand is required for lighting, changing the illumination system from fluorescent to LED has a great benefit at low cost. In fact, the solution with electric heating, HP and LED (see light gray circle marker) is close to the Pareto front in all the climates for both E_{EL} and PE savings plots. The same technology with PV (square light gray marker) is close to the Pareto front only for Rome. Since here, the heating demand is almost zero, the HP technology appears between the cost optimal solutions only when it is combined with PV and LED or PV, LED and battery. The reversible On/Off HP (for heating and cooling) either combined or not with LED, is always between the best solutions for the climate of Stockholm and Stuttgart. When the renovation package involving electric heating, On/Off cooling HP and

LED (see light gray circle marker) is compared with On/Off HP H/C (see yellow circle marker), in Stuttgart and Stockholm, it is noteworthy that the scenario for evaluation of the energy savings (i.e. E_{EL} or $PE_{10-30-30}$) might change the ranking of the solutions. In Fig. 6.A and Fig. 7.F, it can be seen that the renovation package with electric heating, On/Off cooling HP and LED (light gray marker) gives the same or even more E_{EL} savings than the On/Off HP H/C, but the situation is reversed when the savings are evaluated in terms of $PE_{10-30-30}$ (see Fig. 6.D and Fig. 7.H). The monthly conversion factors of the 10-30-30 scenario are almost zero during summer therefore the savings during the wintertime have higher impact on the calculated yearly energy savings. When the PV is considered together with the HP and LED with or without battery (see square and asterisk light blue markers) these solutions are cost optimal in all the climates.

The Pareto front highlights a set of cost optimal solutions from which one renovation package has to be selected based on economic restrictions and other parameters (e.g. thermal and visual comfort, quickness of the retrofitting, personal preferences, etc.). But there are some clear and remarkable trends that can be noted: in Stockholm and Stuttgart the solution with reversible On/Off HP_{ip} H/C + LED have the same cost but guarantee higher energy savings with respect to other solutions such as reversible On/Off HP_{ip} H/C and El. Heating + On/Off HP_{ip} + LED. Adding PV increases the energy savings but also the cost therefore the selection of this solution depend on the economic restriction. Adding battery only slightly increases the energy savings while the cost substantially increases. In Rome El. Heating + On/Off HP_{ip} + LED with or without PV allows to keep the additional cost near to zero enabling high-energy savings.

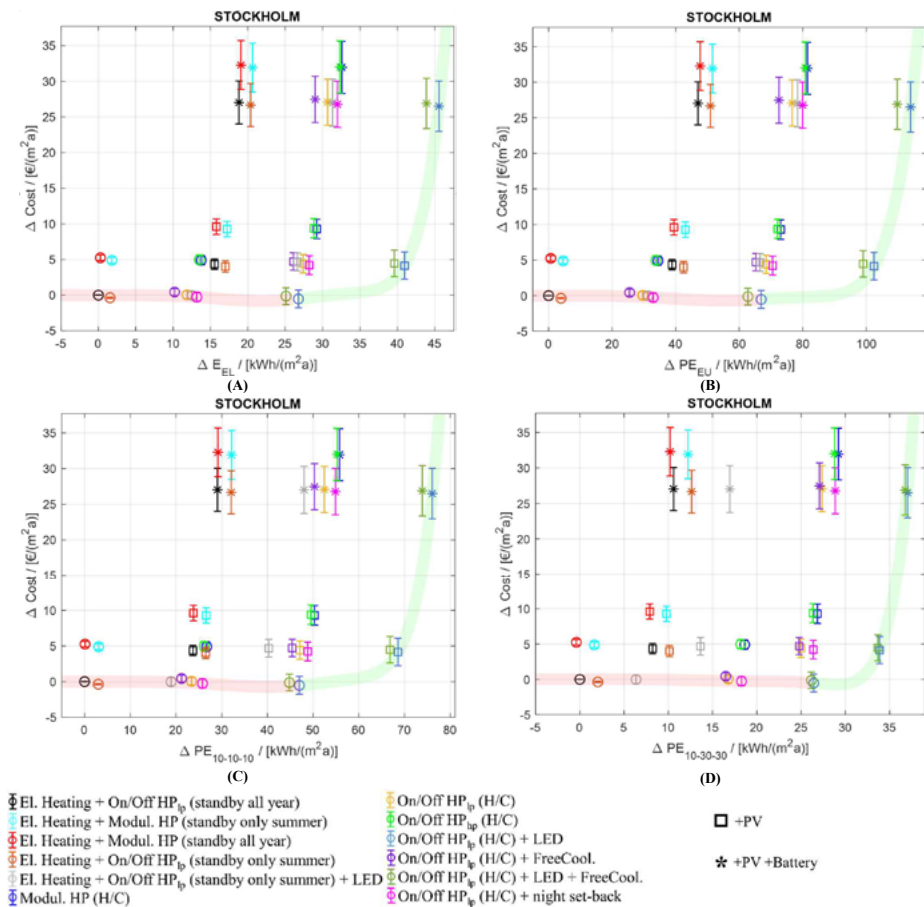


Fig. 6. Savings in terms of (A) Electric energy, (B) Primary energy according to EU conversion factor, (C) Primary energy according to 10-10-10 scenario conversion factors, (D) Primary energy according to 10-30-30 scenario conversion factors vs additional cost of the analysed technologies for the climate of Stockholm

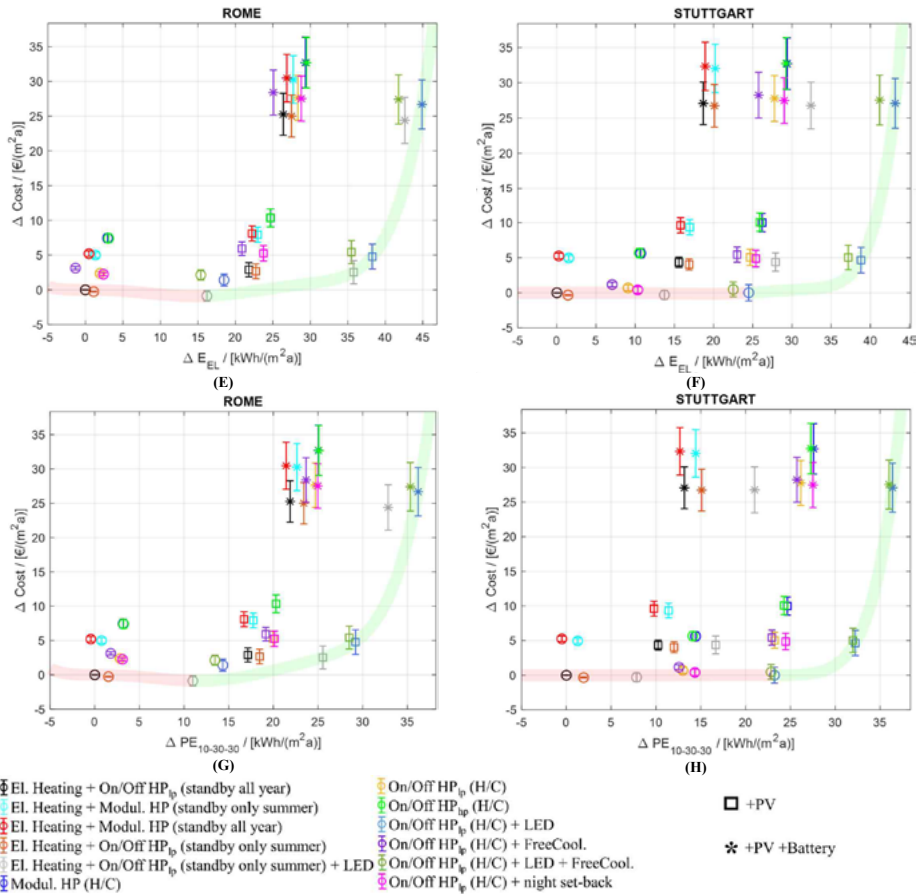


Fig. 7. Savings in terms of (E,F) Electric energy and (G,H) Primary energy according to 10-30-30 scenario conversion factors vs additional cost of the analysed technologies for the climate of Rome and Stuttgart respectively.

Table 6 shows the yearly heating and cooling demands and electricity consumptions for Rome, Stuttgart and Stockholm. Using the HP instead of the electric heating saves around 15% in terms of electricity demand in Stuttgart and Stockholm. The heating demand slightly increases and the cooling demand substantially decreases together with the electricity demand when LED technology is considered. Adding the free cooling to the On/Off HP (H/C) case, reduces the cooling demand while slightly increases the total electricity consumption, this effect is caused by the increased electricity demand of the fans. The night set-back, compared to the case with On/Off HP (H/C), slightly reduces the electricity demand only in Stuttgart and Stockholm.

Table 6. Annual heating, cooling demand and electricity consumption for the climates of Rome, Stuttgart and Stockholm.

	Heating demand [kWh _{th} /(m²a)]			Cooling demand [kWh _{th} /(m²a)]			Total Electricity demand [kWh _{el} /(m²a)]		
	Rome	Stuttg.	Stock.	Rome	Stuttg.	Stock.	Rome	Stuttg.	Stock.
El. Heating+On/Off HP (standby all year)	2.7	13.1	17.2	32.7	26.0	24.5	63.8	73.8	79.0
Modul. HP (H/C)	3.1	13.5	17.6	33.4	26.7	25.0	60.8	63.1	65.2
On/Off HP _{hp} (H/C)	2.7	13.1	17.2	32.7	26.0	24.5	61.8	64.7	67.1
On/Off HP _{hp} (H/C) + LED	4.7	17.5	22.8	24.6	19.7	18.7	45.3	49.3	52.2
On/Off HP _{hp} (H/C) + FreeCool	2.8	13.1	17.3	24.9	17.0	14.3	65.1	66.8	68.8
On/Off HP _{hp} (H/C) + LED + FreeCool	4.7	17.5	22.9	17.8	12.0	9.8	48.4	51.3	53.9
On/Off HP _{hp} (H/C) + night set-back	2.2	10.2	14.0	31.3	24.2	23.0	61.4	63.5	65.8

4. Conclusions

Different technologies applicable for the decentral renovation of a typical office building (cell) are evaluated considering, both economic feasibility and environmental impact for the climates of Rome, Stuttgart and Stockholm by means of dynamic building and HVAC simulations. The cost analysis is based on the equivalent annual cost (EAC) and a sensitivity analysis is performed in order to assess the influence of the used inputs on the results. The environmental impact is evaluated in terms of electricity demand and total primary energy (PE) savings calculated with a constant and monthly conversion factors representing different scenarios with different share of renewables in the electricity mix (i.e. 10-10-10: 10 % hydro, 10 % wind, 10 % PV and 70 % fossil and 10-30-30: 10 % hydro, 30 % wind, 30 % PV and 30 % fossil). In this specific case study, since all the analyzed technologies require electricity as input, the same conclusion can be derived using the energy savings expressed in terms of electricity or total PE calculated with a constant conversion factor while the results might change if monthly conversion factors for different renewables scenarios are used. In fact, the renovation package with electric heating and LED has the same (in Stockholm) or higher (in Stuttgart) electricity savings than the On/Off HP for heating and cooling without LED but the situation is reversed when the savings are evaluated in terms of PE calculated with the conversion factor of the 10-30-30 scenario. The renovation packages allowing high-energy savings with low additional cost are represented, in Stockholm and Stuttgart, by HP in combination or not with LED and PV and in Rome, by LED and PV in combination with electric heating. Battery in combination with PV, HP and LED brings, in all the climates, additional energy savings with high additional cost. Technologies, which will lead to higher savings in winter with lower availability of renewables and generally higher loads, will be more valuable and this can be quantified by the proposed method.

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