Low-energy cooling and ventilation refurbishments for buildings in a Mediterranean climate

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ABSTRACT

In view of the ageing domestic building stock and increasing reliance on fossil fuels for cooling and ventilation of buildings, there is an urgent need for improved design knowledge and sustainable measures such as natural ventilation and passive cooling to mitigate climate change and future proof the built environment. This paper forms an appraisal of a range of low-energy refurbishment measures, i.e. building design alterations and passive systems, which were employed and evaluated in an apartment building in Greece. The applicability of these in domestic buildings in hot climates is assessed and their design implications evaluated. Implementation of wind-catchers, dynamic façades, and evaporative cooling had the highest ventilation and cooling potential, while improvements of the interior layout to allow for new airflow paths could provide further cooling to spaces and solutions to safety.

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Introduction

In view of the existing, ageing domestic building stock and increasing reliance on fossil fuels for cooling and ventilation of buildings, there is an urgent need for improved design knowledge and sustainable measures to mitigate climate change and future proof the built environment. In Europe, residential buildings make up most of the built environment’s floor area, reaching up to 85% in Southern European counties, which could allow for energy savings through low-energy refurbishments (European Commission, n.d.). Natural ventilation and passive cooling can ensure occupants’ thermal comfort expectations are met, whilst reducing our reliance on mechanical systems and increasing the value (e.g. life span and energy ratings) of existing properties (Santamouris & Wouters, 2006; Spentzou, 2015).

Natural ventilation can improve indoor air quality through removal of stale and unhealthy air and provision of fresh air, whilst consuming less energy compared to mechanically operated buildings (Dhaka, Mathur, Brager, & Honnegeri, 2015), which is particularly important when ensuring no transmission of airborne viruses. Despite the potential of passive techniques and vernacular architecture knowledge, occupants continue to rely on mechanical means to ensure comfort due to ease of use, higher incomes and high efficiency of a/c units, and inadequate and inconsiderate building design (Lundgren-Kownacki, Hornyanszky, Chu, Olsson, & Becker, 2018; Santamouris & Wouters, 2006). Consequently, air conditioning installations are the common practice, particularly of split units in domestic buildings across the Mediterranean (Yun & Steemers, 2011). Heat waves in hot climates result in
significant increases of the cooling energy demand and can disrupt supply; whilst low indoor air quality affects the energy poor and ageing population (Macintyre & Heaviside, 2019).

In cities, ventilation through conventional windows and doors is not always feasible due to the high density of buildings and design restrictions that typically allow for only single-side ventilation. Energy refurbishments design guidance can be valuable in the hands of developers, architects, and homeowners, for current and future climates, assisting in developing design solutions.

In this paper, an appraisal of a range of low-energy refurbishment measures, i.e. building design alterations and passive systems, is provided, which reflects on findings from an extensive literature review, elite semi-structured interviews with industry experts, and detailed indoor environmental quality (IEQ) evaluations of selected low energy-measures in a case study building. The practicalities and design implications of low-energy refurbishment measures are considered with regards to their performance, which was predicted through their implementation in an existing domestic building in Greece and tested with computer simulations (i.e. computational fluid dynamics CFD, and dynamic thermal modelling DTM). Extensive CFD of the outdoor environment (i.e. air flow at neighbourhood scale) under all prevailing wind directions and speeds enabled derivation of pressure input parameters for the openings of the indoor building environment CFD models, which determined indoor ventilation characteristics, in (Spentzou, Cook, & Emmitt, 2019). DTM was used to evaluate thermal comfort and passive cooling performance over annual cycles at one-hour intervals, presented in (Spentzou, Cook, & Emmitt, 2018). The objective of this paper is to synthesise those findings and establish low energy refurbishment design guidance for use by researchers and practitioners. This could facilitate large- or small-scale energy refurbishments of domestic buildings in hot climates. The guidance is focused on the passive measures that offer free energy from the environment; reduce dependency on delivered energy formed within active designs (i.e. fossil fuel and renewables); and can be implemented in existing urban residencies. This is complementary to the energy efficiency standards and regulations provided by respective authorities, thus should not be treated as a generalised answer on ways to design, as each building must be viewed individually and within its context.

Low-energy refurbishment measures

Natural ventilation and passive cooling strategies can be applicable in existing buildings and allow for significant energy savings (Santamouris & Kolokotsa, 2013). Several low-energy measures with demonstrable ability to ensure occupants’ comfort have been highlighted in the literature and are presented here. These would require adjustments to suit individual buildings and architectural styles, to ensure performance efficiency.

Ventilation and opening operation

Ventilation through building openings is the most common means to provide fresh air and remove stale, typically through single or cross ventilation in urban apartments, and facilitated by the internal doors. Single-sided ventilation is common in urban apartments with one exposed façade (Visagavel & Srinivasan, 2009). This could be improved by exploitation of façade relief elements, e.g. opening configurations, wing walls, balconies, overhangs and shadings (Mohamed, King, Behnia, & Prasad, 2014).

Apartment buildings in Greece have only two exposed façades facing the main road and a rear internal courtyard. Most apartments utilise single-side ventilation, while some cross-ventilation (Niachou, Hassid, Santamouris, & Livada, 2005). To allow for removal of pollutants and stale air from the deeper spaces, a system of light-wells is typically designed (Papamanolis, 2006). These run along the building height from ground level to the top of the building, intersecting all floors.

Operation of building openings in response to occupants’ needs, indoor/outdoor air properties and time of day can provide natural ventilation, passive cooling and have considerable effect on cooling/heating loads (Angelopoulos, Cook, Spentzou, & Shukla, 2018; Curado, Freitas, & Ramos,
Night ventilative cooling is suitable in regions with lower night temperatures (i.e. below 22°C) as the efficiency of the strategy increases with the reduction in night DBTs, and can counterbalance up to 90% of the need for mechanical cooling (Graça, Chen, Glicksman, & Norford, 2002). For daytime temperatures above 36°C, passive cooling should be considered in addition to night ventilation (Givoni, 1994). Automation of internal and external openings could achieve optimal thermal comfort performance in response to indoor-outdoor temperature differences, solar gains, wind-speeds, internal heat gains, privacy and security.

**Wind-catchers**

Wind-catchers are examples of vernacular architecture that utilise pressure differences across the building surfaces and maximise the driving pressures for ventilation (Hughes, Calautit, & Ghani, 2012). Wind-catchers capture wind at high elevations and channel it down to the occupied spaces (Dehghan, Esfeh, & Manshadi, 2013); operating as both inlet and/or exhaust, during wind and/or buoyancy driving pressures (Calautit, Hughes, & Ghani, 2012). Their performance is influenced by the tower’s shape, height, position, size and number of the openings, and wind incidents (Dehghan et al., 2013).

Wind-catchers with four openings and separated channels have often been employed in areas without prevailing wind (Montazeri, 2011). Calautit et al. (2012) proposed a new, sustainable design able to increase indoor air velocities by more than 60%. Mavrogianni and Mumovic (2010) evaluated the performance of wind-catchers in classrooms and demonstrated potential in meeting pupils’ indoor air quality requirements.

With total height not exceeding that allowed for chimneys, as dictated by building regulations, installation of these in existing buildings marginally disrupt occupants. Designing wind-catchers at the building façades can offer complementary benefits; provided their total cross-sectional area falls within the balcony area, regulations would be met, and planning permission granted. A four-directional wind-catcher, like the proposed design in Figure 1 could capture wind from all directions and allow for stale air to escape.

**Dynamic façades**

Shading devices, common in hot climates, are typically in the form of shutters and retractable canvas awnings. However, their manual operation relies on occupants’ awareness of heat mitigation measures and availability, e.g. they are typically left fully closed/open throughout the day. Controlled operation of shading can be achieved in the form of dynamic façades that operate in response to air temperature, humidity and solar radiation (Hammad & Abu-Hijleh, 2010). Double-skin façades (DSF)

Figure 1. Three-dimensional representation of a proposed wind catcher design with operable louvres closed (a), open (b) and cross section showing internal partitions (c).
have been used in colder climates, although can also perform well in hot climates (Barbosa & Ip, 2014). DSFs usually comprise a pair of glass skins and sun-shading systems (venetian blinds) located on the cavity. Dynamic façades are based on the principles of DSFs, consisting of multiple layers of skins (Zhou & Chen, 2010). The exterior skin layer could be replaced by a layer of shading systems to form a dynamic façade that provides a semi-enclosed environment, shading and natural ventilation of the spaces (Spentzou, 2015). For the research reported here, dynamic façades are considered as the second layer of controlled shading devices at a short distance from the openings, which allow for solar gains reductions and ventilation rates increases.

Balconies can contribute to higher façade wind pressures and provide cross ventilation, although they can impair single-sided ventilation (Mohamed et al., 2014). Wing-walls, which are vertical fins that channel air to the interior of spaces, can sufficiently increase ventilation rates and ensure up to 25% less A/C operation (Mak, Niu, Lee, & Chan, 2007; Yik & Lun, 2010). Combined use of wing-walls and overhangs could reduce indoor solar radiation (Koinakis, 2005). All these elements can be used to form dynamic façades in existing buildings by ensuring minimum occupant disruption and cost.

Passive down-draught evaporative cooling towers (PDECT)

All low-energy measures addressed thus far can reduce indoor temperatures by removing stale air and by reducing heat gains; however, additional means are required for temperature reductions below the outdoor temperatures. Evaporative cooling utilises the energy required to convert water from liquid to vapour, the latent heat of vaporisation, and is achieved when air contacts water in evaporation. This process could be adiabatic when no energy is added or extracted from the system. Its efficiency depends on the temperature, moisture content, velocity of ventilated air, the temperature of the water or of the wet surface (Santamouris & Wouters, 2006), and the design characteristics of the system.

Passive down-draught evaporative cooling towers (PDECT or PDE Ct) are advanced wind-catcher designs widely used in vernacular middle-east architecture, trapping air from rooftop levels and providing passive cooling by water evaporation (Ford, Schiano-Phan, & Vallejo, 2019). The performance of these has been widely evaluated, considering them a viable alternative to traditional mechanical cooling systems in dwellings in hot and dry climates (Hughes et al., 2012). Mediterranean European countries are zones of medium to very high PDE Ct applicability (for DBT above 25°C) (Salmeron et al., 2012). Investigations in the southern-European countries identified optimal conditions for the PDE Ct applicability which if implemented in domestic buildings could provide significant energy and carbon savings (Ford et al., 2019). However, the risk of legionella that has previously been reported for this system should be carefully mitigated to allow for optimum operation (Martinez, 2000) and in accordance to CIBSE (2013).

Building design: interior layout

It is important to recognise the impact of the interior layout of buildings and location/size of internal and external openings on the ventilation performance of any of the systems/strategies mentioned thus far. Although most building elements are fixed, for a successful low-energy refurbishment, alteration of these should be considered. These could be in the form of relocating internal doors or addition of new narrow internal openings to alter the internal air flow paths and reduce/move under-ventilated zones in the living spaces.

Methodology

The research reported here aims to deliver valuable design guidance for existing but also new residential buildings through building operation, passive systems and building design. Selecting low-energy refurbishment measures should be based on a number of criteria, including: climate
applicability; design flexibility; ease of implementation with minimum disruption to current occupants; ease of use; energy performance; and thermal comfort potential. The low-energy refurbishment measures identified are evaluated against these criteria. Both quantitative and qualitative data have been collected: qualitative in the form of elite semi-structured interviews, and quantitative in the form of a programme of computational simulations. These were combined with literature findings and allowed for performance evaluation of low-energy measures and development of guidance and recommendations for future refurbishment projects.

The programme of computational simulations allowed several low-energy refurbishment measures to be evaluated in the context of an existing case study building (shown in Figure 2). The objective of this study was to synthesise the outputs of the technical investigation in a single case study, in order to allow for exploration of the potential feasibility of selected refurbishment measures for a larger scale and diversity of buildings in a qualitative manner.

The low-energy refurbishment measures evaluated were:

1. Optimum operation of building openings, internal and external, to achieve single-sided and cross ventilation;
2. Capture of high-elevation winds through wind-catchers;
3. Adaptable shading through operable dynamic façades and façade relief techniques;
4. Passive cooling through water evaporation techniques (Passive Downdraught Evaporative Cooling towers – PDECt); and
5. Introduction of new internal airflow paths.

The strategies detailed are the most suitable measures identified by the authors through an extensive literature review (Spentzou, 2015), but not the only available measures. The way in which they can be exploited and designed is not limited to what is presented here. Evaluation of their performance in existing buildings is challenging and results from this study are only indicative as the performance of any refurbishment measure is subject to building design, microclimate, operation and occupancy. Utilisation of the proposed strategies would aim to reduce cooling loads of existing dwellings and offer occupant comfort during wintertime. Further, using energy efficiency measures addressing the building fabric, such as insulation and glazing properties, was out of scope of this research as these have been extensively evaluated by others in the climate and building typologies studied (Dascalaki, Balaras, Kontoyiannidis, & Droutsa, 2016; Domínguez-Amarillo, Fernández-Agüera, Sendra, & Roaf, 2019; Droutsa, Kontoyiannidis, Dascalaki, & Balaras, 2016). The refurbishment strategies were selected according to a preliminary climate evaluation using the Adaptive-Comfort model in ASHRAE Standard 55-2010, indicating their suitability for the case study and potential to deliver passive cooling and/or natural ventilation. A psychrometric chart (Figure 3) was developed for Athens through Climate

![Figure 2](image_url). Street view of the case study building (by authors).
Consultant (Liggett & Milne, 2018). For the cooling season (May-September) (Spentzou, 2015), comfort hours account for about 40% of the time. Passive measures can ensure occupant thermal comfort for more than 80% of the time, whereas addition of evaporative cooling and use of fans for up to 90% of the time. This indicates a significant opportunity for energy reductions that could be achieved through the identified low-energy measures. ASHRAE Standard 55-2010 was used for the initial evaluation of the climate due to its availability and as a visualisation aid for the performance potential of the different passive means. A comparison between different comfort models in Spentzou (2015) including the adaptive comfort model developed for Greece (SCATs project) has shown that Standard 55-2010 is the most conservative with regards to allowing for higher temperatures and thus the predictions for the applicability of the studied strategies could be even more substantial.

For refurbishment initiatives, apart from the construction cost, which has been found to vary according to local practices, disruption should also be considered. Literature and findings of this research support the development of a low-energy refurbishment guide, which will illustrate the potential performance of retrofits in similar buildings and climates.

Case study building and strategies

The case study building is representative of over four-million buildings in Greece and a significantly energy consuming building typology (Droutsa et al., 2016; Spentzou, 2015). The climate of Athens is marine and is classified into the Mediterranean climate type of Csa (56%) of Köppen Climate Classification (Gialamas, 2011). The low-energy refurbishment strategies identified have the highest potential for wide-spread implementation in other hot climates and a range of analogous building typologies, and lead to significant energy consumption reductions through large-scale refurbishment projects.

The apartment building (Figure 2) was constructed in the 1970s, is in a densely populated area. Figure 4 shows the layout of a selected apartment, with the potential zones of interventions highlighted and the type of low-energy measures that could be implemented. Two bedrooms are directly connected to the balcony through patio doors. This space could facilitate as a buffer zone for a dynamic façade. At the rear, the kitchen and bathroom are connected to a light-well that also performs as a ventilation shaft. Within the false ceiling of the bathroom there is an ancillary space with free height of 1.1 m; typical storage in apartments, is proposed to be used as a way to access the light-well bypassing the bathroom and thus creating new internal airflow paths. A living space at the rear has no direct or indirect access to outdoor air. Wind-catchers could be designed within the core of existing building by utilising light-wells or attached to the façades as proposed in Figure 5.
Greece is characterised with the highest winds in the Mediterranean; however, in urban sites the low ratio of the urban streets width to the buildings’ height (about 0.6) results in reduced airflows at street level, (low wind pressures at the façades) and small potential for natural ventilation via openings (Papamanolis, 2000). However, high winds dominate at the rooftop level, offering efficient operation of wind-catchers. For the case study building, the prevailing wind-direction was north; however, capturing wind from all directions was considered important. Three identical four-directional wind-catchers were implemented on the top part of the existing light-wells, each assisting the ventilation of two apartments on each floor across the building (Figure 6). Sizing of the wind-catchers was governed by the existing building design and form, aiming to deliver the least occupant disruption and alteration of the building’s architectural characteristics. The area of the inlets

Figure 4. Layout of the case study apartment showing the location of current openings and the identified appropriate locations for low-energy refurbishment measures.

Figure 5. Plan view drawing of a typical floor of the case study building showing the location of 3 lightwells and the potential locations for the design of wind-catchers (11).
(2.2m²) was twice the area of the internal connecting opening (outlet). This was to allow for two apartments to simultaneously use the wind-catcher. The wind-catcher top inlets/outlets operated according to the wind-direction, indoor and outdoor air properties, and occupant’s preferences (e.g. need for night-ventilation). The four-directional inlets operated in pairs (opposite openings), thus, as a two-directional wind-catcher according to the prevailing wind direction. The perpendicular to the prevailing wind channel dampers and top inlets would automatically shut, ensuring no interference from the side winds. This was successfully simulated using DTM.

A dynamic façade was proposed with the use of a set of operable louvres located at the edge of the balconies (Figure 7). These replace the traditionally used canvas awnings, creating a semi-outdoor space of air circulation and buffer zones. The louvre material selected was extruded aluminium alloy, although they could be customised via a wide variety of materials (e.g. glass, wood, and glass with integrated photovoltaic cells) subject to architectural and thermal/daylighting...
requirements. The carrier system integrates a central aluminium torsion tube along the length of the louvres assisting their rotational operation. Partition walls as wingwalls, perpendicular to the building and the dynamic façade, were designed between all apartments and delineate the property boundaries. Their height is equal to the floor to ceiling height and length equal to balcony depth. Sizing the louvres was dictated by dividing the height of the opening by the width of louvres; this is applicable to east and west facing elevations (Palmero-Marrero & Oliveira, 2010).

The dynamic façade was divided into three arrays of louvres that were independently controlled, offering operation flexibility and aesthetics. The three groups of louvres create multiple operational patterns in respect to solar radiation, glare, privacy, time, outdoor air properties, and ventilation needs, and occupant’s preferences in order to provide optimum control. They adjust as: fully open; partially; top and bottom; inclined; horizontal or vertical arrangement etc. (Figure 8). Operation in response to time offers solar gains control (e.g. only bottom open), privacy (e.g. only top open) in addition to natural ventilation. The façade could allow fresh air to be introduced in the spaces by the lower open louvres, while the exhaust is discharged from the top, with the middle remaining closed for glare control and privacy. An example operation is shown in Figure 9.

![Cross-sections of the balcony and the dynamic façade under different operations.](image)

**Figure 8.** Cross-sections of the balcony and the dynamic façade under different operations.

![South elevation of the case study building showing the operation of the dynamic façade.](image)

**Figure 9.** South elevation of the case study building showing the operation of the dynamic façade.
Simulation approach

All selected low-energy measures were evaluated for a single unit under the typical climate conditions. The refurbishment guidance provided is principally based on simulation results produced using the computational fluid dynamics (CFD) code PHOENICS using the finite-volume method and a structured grid. The building was modelled within the 9 urban blocks, with 103 residential buildings, to allow for prediction of detailed flows around and within the living spaces, using a de-coupling approach. Steady-state simulations investigated the typical dry-bulb temperature (26°C), under low-average-highest wind speeds (buoyancy, 3.6 and 7 m/s) and three wind directions, in response to a climate study performed. Further CFD modelling details are described in Spentzou et al. (2019), including internal/external domains, mesh sensitivity studies, turbulence model, convergence criteria used and validation of the code. Further, the performance of low-energy retrofits in the case study using dynamic thermal modelling (DTM) was investigated, in order to predict the temporal changes in indoor air quality within specific zones over cooling period in a typical year (i.e. hourly intervals). Using DTM the performance of the strategies was evaluated for specific occupancy and building operation scenarios. Details of the DTM modelling approach employed are described in Spentzou et al. (2018). Outputs of both CFD and DTM studies not previously published, are synthesised here aiming to identify the broad feasibility of selected measures for building energy refurbishments across similar buildings and climates.

Reflecting on expert’s views

Elite exploratory semi-structured interviews solicited the opinions and advice of five with different backgrounds and experience in the field in Greece, regarding: construction sector activity and growth; and the implementation potential of low-energy and passive ventilation/cooling systems in buildings.

Elite interviewing is a widely used method for collecting primary data from those with expertise (Morris, 2009). The questions concerned the personal experience, opinion, knowledge, and sensory aspects of each interviewee. They were interviewed, through the phone, email and in person during the duration of this research programme completed in 2015. The questions were modified according to the discipline of each interviewee: two academics with research expertise in building energy; two architects; and a domestic buildings structural engineer. The key findings are summarised below; further details are in Spentzou (2015).

The lack of growth in the construction sector due to the financial crisis in Greece was a common throughout the responses. Accordingly, the construction of multi-storey buildings, key typology of all urban environments in Greece, has stopped and refurbishments would drive the construction activity and market over the coming years. This emphasises the significance and timeliness of multi-storey energy refurbishments.

Designing energy efficient new builds, typically about 0.1% of the building stock, would deliver insignificant energy consumption reductions. The need to redesign existing buildings to meet the increasing cooling demand and comply with international energy standards was emphasised. The urgency of low-energy refurbishments of domestic buildings constructed as early as the 1950s should, however, enhance the building aesthetics and ensure harmony with the existing architecture, which reinforces the representativeness of the selected case study building.

Interviewees reflected on the severity of fuel poverty in the country and the inability of the low-income households to obtain thermal comfort, emphasising the importance of low-energy refurbishments. However, through all interviews, it was evident that despite the widespread need for knowledge transfer on energy saving measures with regards to cooling/heating and ventilation, designers have limited understanding of the various passive techniques and thus low-energy design guidance would be a valuable decision support tool.
Low-energy measures: refurbishment performance of a case study building

The low-energy refurbishment measures identified in literature were redesigned to meet the design and performance criteria of the case study building. The following sections discuss the performance of each low-energy refurbishment measure using simulation results, using steady-state CFD for average and extreme climatic conditions during the cooling period, and DTM simulations for a yearlong hourly performance. Each proposed strategy could be further individually explored to allow for the identification of the most optimal approach for the individual characteristics of each building case. The graphical figures presented offer an understanding of the operation of the strategies and do not aim to quantify their ventilation performance or energy savings, as these would significantly vary from building to building, even amongst different apartments of each building (Curado et al., 2015).

Ventilation and opening operation

At the case study building, day and night ventilation was achieved through the control of external and internal openings and internal doors. When the light-well openings remain closed, openings on the external walls facilitate single-sided ventilation (Figure 10). Under strong wind incidents, this offered average indoor air temperatures of less than 2°C above the external, and less than 0.2 m/s indoor air velocities; however, these are lower than the acceptable levels required for occupant comfort according to CIBSE (2016). Cross ventilation via the light-well delivered higher ventilation rates and average velocities of approximately 0.6 m/s in the bedrooms, 1.5 m/s in the kitchen area and below 0.20 m/s in the living room and contributed to significant temperature reductions.

Night-time ventilation, through controlled operation of openings in response to internal-external air temperature differences and CO₂ levels in the spaces, offers reductions of internal temperatures during the night and removal of stale air, and can ensure lower temperatures for the following morning (Spentzou et al., 2018). For the case study, night ventilation reduced the indoor temperatures during the morning hours and the peak temperatures of the following day by 3°C, relative to not using night ventilation. The performance of night ventilation was consistent with that reported by others (Santamouris & Kolokotsa, 2013). However, as has been reported in the literature, in areas with daytime temperatures above 36°C, passive cooling strategies should additionally be considered (Givoni, 1994).

![Figure 10. Streamlines of the airflow movement in the spaces, showing the starting and final point of the flow single-sided (left) and cross ventilation (right), for 7 m/s north wind and air temperature of 26°C.](image-url)
Wind-catcher

The wind-catcher offered more than double the ventilation rates predicted for simple cross-ventilation and reduced temperatures in the living spaces (Figure 11). Wind-catchers performed well at the core spaces without external openings. As shown in Figure 12, the ventilation and cooling performance of the wind-catcher in the case study building varies across the building floors with higher indoor air temperatures predicted at the lower floors (i.e. the apartment studied), in response to the higher indoor air velocities at the top floors due to the proximity to the wind-catcher inlets/outlets. It is important to optimise wind-catcher designs to increase their performance throughout the building height.

Dynamic façades

CFD simulation results for a single typical climate scenario (3.6 m/s east wind at 26°C) and three operations of the louvres are presented in Figure 13, showing (i) all louvres at the ‘fully open’ position, (ii) the ‘upper’ section of louvres open only, and (iii) the ‘upper and lower’ parts open, respectively. This is a highly computationally demanding simulation scenario due to the mesh size in the louvres. The operation of (ii) and (iii) resulted in increased ventilation rates, by a factor of 2, relative to (i). The ‘upper and lower’ operation provided homogenous air flow distribution across the spaces relative to the other two and would be the most recommended configuration in this case.

Predicted indoor air temperature and velocities along a defined line (at 1.5 m height above the floor) across the apartment from the façade, through the bedroom to the rear kitchen wall, were plotted for the three louvre operations in Figure 14. Cross-ventilation is achieved through the rear shaft allowing high louver velocities in the kitchen. Comparable results were predicted during the

Figure 11. Streamlines of the airflow movement in the spaces, showing inflow through the wind-catcher (blue) and outflow through the patio openings (red) (7 m/s north wind and outdoor temperature 26°C).
upper and lower strategies. The fully open position produced the least temperature reductions in the front spaces; emphasising the potential of customisable operation of louvres to improve ventilation performance.

Figure 12. 3D representation of the building showing temperature distribution on 2D planes across four apartments and the velocity distribution on a 2D representation of the building during (north wind of 7 m/s and 26°C air temperature).

Figure 13. Velocity contours and vectors at y, z cross section of the second bedroom, balcony and dynamic façade. All louvres fully open (a), upper and lower open (b) and only upper open (c) according to Figure 8 (3.6 m/s east wind at 26°C).

‘upper and lower’ and ‘upper’ strategies. The ‘fully open’ position produced the least temperature reductions in the front spaces; emphasising the potential of customisable operation of louvres to improve ventilation performance.

Figure 14. Predicted indoor air velocity (left) and temperatures (right) at 100 points along two lines at 1.5 m height from (3.6, 0, 1.5) to (3.6, 9.3, 1.5) from the façade to the rear spaces, for 3 louvre positions.
Operable louvres would become closed or partially closed during the incidents of high solar gains, thus, reducing the ventilation potential of the living spaces and compromise comfort in living spaces. Implementation of façade wind-catchers could be a feasible solution, as the balcony could facilitate the flow of fresh air from wind-catchers and channel it to the living spaces through the balcony openings (Figure 15). The exploratory performance evaluation of this ventilation strategy for the case study apartment, included the design of a wind-catcher of $1 \times 1.6 \text{ m}$ cross section. CFD simulations showed significant ventilation benefits from the simultaneous operation of two wind-catchers, allowing for one to be used as inlet and the other as outlet, or both as inlets and outlets. In the conditions under which the low-energy refurbishment measures were tested (wind-driven flow, north wind, 7 m/s wind speed, 26°C DBT), the façade wind-catcher operated as an inlet, delivering fresh air into the spaces. Stale air escaped from the core wind-catcher. Captured air at the top inlets of the façade wind-catcher was channelled into the first and then the second bedroom when the dynamic façade louvres were closed, shown in Figure 16 and Figure 17. This considerably improved the fresh air distribution in the front spaces and the increased ventilation rates led to reductions in air temperature in the rear spaces.

Figure 15. South elevation of the case study building showing the façade wind-catchers and the dynamic façade.

Figure 16. Temperature (left) and velocity (right) distribution on 2D-plane at the selected apartment (north, 7 m/s wind and 26°C air temperature).
Passive downdraught evaporative cooling towers were able to cool the living spaces below the outdoor temperature, and offer substantially greater temperature reductions relative to the other ventilation strategies. This is particularly important if the future climate projections are considered as conventional refurbishment measures (e.g. thermal insulations) might not offer the desired reductions in the cooling demand of the oldest housing stock (Domínguez-Amarillo et al., 2019). Indoor air temperatures and velocity distributions were predicted at a horizontal plane at 1.5 m height above each apartment’s floor along the building height (Table 1). Differences in indoor air temperatures varied between 0.3°C and 2°C across the four apartments, with the least difference predicted during buoyancy and wind driven flows of 7 m/s wind speed. These are comparable to data by Curado et al. (2015) showing vertical alignment of apartments resulting to temperature differences of up to 1°C, and how occupancy variations can increase this up to 4°C. The cooling performance of the PDEC reduced towards the upper floors due to the reduced length of the water evaporation zone. A possible solution to this would be to create two zones of water evaporation within the same shaft, by installing two spraying systems. One would assist the upper two apartments (larger volume of water) and one at a lower level assisting the lower apartments.

The PDECt strategy delivered greater cooling at the lower apartments although provided higher ventilation rates at the top floor apartment due to its proximity to the evaporation zone. During high wind speeds, the cooling performance of the top floor with PDECt was similar to the wind-catcher.

**Table 1.** Predicted indoor average air temperatures and velocities at a horizontal plane (1.5 m height above each apartment floor) for the natural ventilation strategies studied at the four apartments.

| Ventilation scenario | 1st floor | 2nd floor | 3rd floor | 4th floor | Max-min difference |
|----------------------|-----------|-----------|-----------|-----------|--------------------|
| WC 26°C North 7 m/s  | °C        | m/s       | °C        | m/s       |                    |
|                      | 26.5      | 0.22      | 26.4      | 0.39      | 0.27               |
| WC 26°C North 3.6 m/s| °C        | m/s       | °C        | m/s       |                    |
|                      | 26.6      | 0.20      | 26.8      | 0.18      | 1.45               |
| WC 26°C Buoyancy     | °C        | m/s       | °C        | m/s       |                    |
|                      | 27.1      | 0.07      | 27.2      | 0.07      | 0.3                |
| PDEC-WC 10L/h 26°C North 7 m/s | °C | m/s | °C | m/s | |
|                      | 24.3      | 0.26      | 25.8      | 0.86      | 2.0                |
alone; however, during low wind speeds, temperatures on the top floor were lower with the PDECt (up to 2°C lower). The PDEC performance varied with the temperature of the water. Higher control of the openings’ operations (simulated as fully open with the same cross-sectional areas at all spaces), particularly of the upper floor apartments, would potentially increase the performance of the ventilation strategies evaluated.

Building design: interior layout

The possibility of creating new airflow paths within the living spaces was explored to increase occupant comfort at targeted zones, this would be subject to individual building designs. The case of utilising unoccupied ancillary spaces on top of the bathroom was considered here.

Any fresh air flowing through the lightwell downwards into the living spaces would pass through the kitchen/bathroom, therefore, quality of fresh air is always compromised. The ancillary space within the bathroom’s false ceiling assisted the ventilation of all living spaces. When internal doors are closed (e.g. for privacy) additional small openings above the bedroom doors offer cross ventilation. Figure 18 shows all new internal openings proposed: two small openings above/side of the bedroom doors; two on the ancillary space (one on the hallway wall and one at the lightwell); and partitions above the false ceiling to channel the flow.

The new airflow paths achieved lower indoor temperatures in the spaces and higher ventilation rates. Airflow distribution through the living spaces and the ancillary space can be seen in Figure 19. This strategy could be an alternative for cross ventilation when internal doors are closed, and as it creates a natural displacement ventilation scenario. The higher-level openings would allow for the removal of the stratified polluted warm air close to the ceiling, and minimise exposure risk to e.g. coronaviruses (covid-19) (Bhagat, Davies Wykes, Dalziel, & Linden, 2020). Further design investigations under various climate conditions would be required for the design and operation optimisation of this strategy.

Discussion

The research reported here shown that climate applicability of passive cooling and ventilation strategies is not enough when deciding suitable refurbishment options but building designs and microclimates should be considered. By investigating the proposed low-energy refurbishment strategies within a case study building, cooling and ventilation trends were predicted that could be used as a general guide in similar refurbishment projects.

The relationship between operative and outdoor running mean temperatures was evaluated for the refurbishment strategies (Figure 20). Average daily values of operative temperatures for four

Figure 18. Three-dimensional representation of the apartment spaces showing the new hallway openings.
strategies (wind-catcher, dynamic façade, wind-catcher and dynamic façade, and interior layout/openings) were found to be within the acceptable comfort limits according to BSEN15251 and the adapted for the Greek climate SCATs (Spentzou, 2015) but high outdoor temperatures. Operative temperatures were below the narrower minimum comfort band, however within the band for existing buildings, with operative temperatures overall within the narrower band for more than 52% of the cooling period. From the four strategies in Figure 20, lowest temperatures by up to 1°C were achieved for the combined operation of the wind-catcher and dynamic façade.

By establishing their cooling potential of the proposed strategies under predominant wind-speeds their refurbishment suitability could be decided. In order to quantitatively assess the performance of the proposed refurbishment strategies, relationships between predicted indoor temperatures under a various wind speeds were established. Figure 21 provides a comparison of their expected performance.

Figure 19. Temperature at 1.5 m (left) and velocity at 2.5 m height (right) contours and vectors on xy plane from the apartment floor during wind-driven ventilation of the 'internal openings' strategy (north, 7 m/s, 26°C).

Figure 20. Relationship between outdoor running mean and operative temperatures for two refurbishment strategies, and comfort bands according to BSEN12521 and SCATs.
Empirical relationships were extrapolated and interpolated from a range of steady-state CFD results; these were in agreement with expected trends and could thus be used to predict ventilation performance behaviours under conditions that were not simulated (Spentzou et al., 2019). Higher wind speeds enhance the cooling performance of the cross-ventilation, wind-catcher, and dynamic façade strategies. Beyond a unique for each strategy threshold wind speed, equilibrium is reached between the internal-external thermal environments. In contrast, the cooling performance of the PDEC strategies reduces as the wind speed increases.

For very low wind speeds the combined dynamic façade and wind-catcher strategy provides up to 1°C lower indoor air temperatures than the cross-ventilation, and the PDECt up to 8°C lower. For average wind speeds (3.6 m/s was the average of the climate studied), the combined dynamic façade and wind-catcher strategy provides up to 0.4°C lower indoor air temperatures than the cross-ventilation and the PDECt up to 3.7°C lower. For higher wind speeds (8 m/s), all strategies apart from the PDECt provided the same amount of natural cooling, which delivered up to 1.9°C lower indoor air temperatures.

The simulations were performed for fully open openings and without taking into consideration the building’s thermal mass. Due to internal heat gains, higher indoor than outdoor air temperatures were predicted for the strategies without evaporative cooling. Under real conditions, the thermal mass would regulate the indoor air temperatures, and therefore the strategies would offer further cooling. However, the relative difference and trends in the performance of the different strategies would remain.

Literature and findings from this research allowed the development of a low-energy refurbishment matrix, shown in Figure 22. This has been drafted in the form of traffic light system, green, orange and red to allow for visual comparison, i.e. ideally the best performing strategy would meet all criteria in the best way (all green); however, a trade between green, orange and red would be made for every refurbishment case. The criteria are not equally weighted, and their significance would vary with every refurbishment building. A cost–benefit analysis could be used to design

![Figure 21. Relationship of wind-speed and difference between indoor and outdoor air temperatures for the low-energy refurbishment strategies.](image-url)
the most effective combination of strategies that meets the specific requirements of each building design, owners’ needs and microclimate. The low-energy refurbishment matrix is an indication of overall performance and could be used as a general guide for refurbishments in similar buildings and climates. The following performance indicators were explored:

(1) **Climate applicability**: The applicability of the different low-energy refurbishment strategies would vary in response to microclimate. The dynamic façade would be more applicable to apartments with South and West facing orientation, for shading during later hours of the day and when the occupants are mostly present. According to the Psychrometric chart (Figure 3), solar shading could ensure up to 30% comfort hours for the climate of Athens; although this is an indicative value, it demonstrates the potential of the dynamic façade in delivering occupant comfort. The climate applicability of the proposed strategies was defined based on studies reported in the literature (Barbosa & Ip, 2014; Calautit et al., 2012; Givoni, 1994; Graça et al., 2002; Hughes et al., 2012; Mavrogianni & Mumovic, 2010; Mohamed et al., 2014; Salmeron et al., 2012; Santamouris, Sfakianaki, & Pavlou, 2010).

(2) **Design flexibility**: The strategies’ design should permit operations according to the changing occupants’ needs (e.g. Angelopoulos et al., 2018). Most of the proposed strategies allow for this. Modification of the interior building design would result in an even more customised building operation and thus less flexibility.

(3) **Disruption**: Alteration of the building design and form to allow for the implementation of the proposed strategies would cause disruption to current occupants, particularly for strategies requiring work in the living spaces (i.e. interior airflow paths) or planning permissions (i.e. dynamic façade).
(4) **Ease of use**: Occupants’ familiarity with conventional systems allows for easier use, at least in the short term. Strategies with increased complexity require automated control for optimum performance, with the option for occupant control when required. However, even for conventional systems deemed to offer ease of use, they perform better during automated control rather than manual control by occupants (Spentzou, 2015), by taking into consideration indoor /outdoor conditions and occupancy and for specific control setpoints (Angelopoulos et al., 2018). Openings control for night-time ventilation has significant cooling benefits and can ensure optimal opening state when occupants are asleep. Occupants would have to adapt to a smarter way to control systems and the building envelope, and automation would increase their ease of use.

(5) **Energy savings**: The energy savings have been defined according to an overview of the reductions in air conditioning usage that they could offer, without disregarding the operational cost. The embodied cost and energy of the materials and systems should be further considered. All proposed strategies are passive or low energy; however, automation of operation would result to some energy usage. PDECt would have the highest operation consumption for the supply of the fan and the water droplet mechanism; however, it is the strategy with the highest cooling potential (Figure 21), thus offers the least reliance on air conditioning.

(6) **Cooling and ventilation performance**: Performance of the proposed strategies varies in response to climatic conditions and occupancy. The solution with the highest cooling and ventilation benefits would combine the most efficient strategies, and would allow each individual strategy to operate under the conditions in which it performs the best. The cooling performance of the strategies was defined according to Figure 21 and work by others previously described (e.g. Ford et al., 2019).

**Conclusions**

The research reported here has reviewed and evaluated the suitability of various low-energy strategies as refurbishment measures in existing urban dwellings, including considerations from a designer’s perspective. Guidance has been established that could facilitate large- or small-scale energy refurbishments of domestic buildings in hot climates focused on passive strategies and natural ventilation.

The proposed strategies have been assessed according to their cooling and ventilation performance and impact on occupant comfort, disruption, and implications for architectural design. These were evaluated for a case study building, typical of Mediterranean architecture. For the climate studied, natural ventilation using building openings should ensure night-ventilative cooling and optimum performance throughout the day, which can only be ensured with automated control customised for the respective occupants needs. Existing ventilation shafts could improve comfort in the core spaces and deliver cross-ventilation; however, implementation of wind-catchers can exploit high-elevation wind speeds and assist removal of stale air from spaces without façade openings. Dynamic façades can ensure solar shading and enhancement of the ventilation rates through flexible operation. Water evaporation measures ensure further cooling to temperatures below the outdoor air temperature and reductions of internal heat gains. The natural cooling performance of the proposed strategies varies significantly for low/no wind speeds, which are typical in urban environments, and up to 9°C. Design based modifications for internal airflow paths could improve ventilation rates when external openings are partially open for safety/privacy. A combination of the proposed strategies according to the building design, occupants needs, and microclimate could ensure the most optimum performance and least disruption for the occupants. A cost–benefit analysis could be used to design the most effective combination of strategies for individual refurbishment projects.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).
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