Simulation aided development of a façade-integrated air handling unit with a thermoelectric heat exchanger

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Abstract. The paper presents a simulation aided development of a new type of a façade-integrated air handling unit for local ventilation of rooms. The unit is developed as a part of the Plug-and-Use (PnU) concept within the H2020 project PLURAL. Unlike conventional local ventilation units designed solely for ventilation, the developed air handling unit has a two-stage heat recovery that combines a passive and an active heat exchanger. The active heat exchanger consists of an array of thermoelectric elements and provides the flexible and energy efficient capability of temperature control of supplied ventilation air. The paper demonstrates the practical use of building energy simulations for the development of the unit. A combined simulation approach was used, while the IDA ICE software addressed the indoor CO_2 concentration and related ventilation volume flow rates used for the TRNSYS software, which predicted energy performance and indoor thermal conditions. In the TRNSYS, a numerical representing the initial prototype of the air handling unit was prepared. This sub-model was integrated into the TRNSYS building model of the real installation demo site, namely, the Terrassa building, Barcelona, Spain. A variant numerical analysis was performed with two different compositions of the building envelope (pre- and post-renovation) and several ventilation control strategies and air handling unit operation settings. The performed simulations were capable to predict the performance of the innovative device in the real-case arrangement, under various scenarios, on the scale of the entire building. The simulation analysis demonstrated that the façade integrated air handling unit can clearly improve the IAQ conditions and reduce the overheating in the case when no other cooling system is available. The simulations provided an important navigation for the design team to further develop the innovative device.

Keywords. PLURAL, local **v**entilation**,** façade unit, thermoelectric cell**,** design, simulation, TRNSYS
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1. Introduction

The implementation of ambitious EU energy efficiency targets within the Renovation Wave Strategy [1] calls for high-performance, cost-effective, and fast renovation solutions to rapidly reduce energy demand of existing building stock [2]. Prefabricated add-on façade modules represent a suitable solution that allows, in addition to increased insulation of the building envelope, the integration of best-practice technologies such as photovoltaic panels or in-facade ventilation units.

The goal of such integration is to upgrade the performance of existing buildings in the shortest possible renovation time, as the prefabrication and modular approach decrease the duration of the on-site production and installation phases, lower the overall cost, ensure maximum comfort standards and at the same time reduce the operational energy consumption. While standard ways of building envelope renovation opting mainly for better energy efficiency (increased insulation, new windows, etc.) may lead to overheating risk and unacceptable IAQ quality [3], the more complex solutions integrate other systems to mitigate these potential risks.

The paper is focused on the simulation aided development of a Plug-and-Use (PnU) façade module providing additional insulation and visual improvement of the building façade and integration of advanced building systems. The module may integrate photovoltaic panels and an air handling unit (AHU) with thermoelectric air-conditioning capability. The prefabricated façade module presented in this study acts as an 'add-on' panel that is mounted on the existing building envelope. The panel development is carried out within the framework of the H2020 project PLURAL (Plug-and-Use Renovation with Adaptable Lightweight Systems), see www.plural-renovation.eu. As the proposed PnU solution combines several non-standard and innovative features, the simulation analysis helps the design team to better understand the overall PnU module performance and the impact to the indoor environment and energy use of the dwelling during the initial design phase, before manufacturing of the prototype and consequent final product. This study is focused mainly on the integrated AHU and its operational regimes. The paper demonstrates the practical use of building energy simulations for the development of the proposed system and prediction of the AHU positive impact on the IAQ and thermal comfort indoors. The developed solution is tested with use of a numerical model of the real demo-site where it will be installed, i.e., Terrassa apartment building located in Barcelona, Spain.

2. Combined simulation approach and simulated scenarios

A combined simulation approach was used to predict airflows and related indoor air quality (IAQ), which is represented by CO_2 concentration here, as well as the energy performance considering the innovative and non-standard components. While the IDA ICE software addressed air-flow network simulation and predicted the indoor CO_2 concentration in the simulated dwellings, TRNSYS software predicted energy performance and thermal comfort. Both simulation software used the same weather file and the boundary conditions of the model, which enabled the combination of the results from the different simulation tools.

The following steps were taken during the combined numerical study, see also Fig. 1, to simulate performance of the two representative flats in the installation demo site of Terrassa building. First, the identical weather file was imported to each software. Second, the IDA ICE software was used to predict the infiltration and related indoor CO_2 concentration in the simulated dwellings for both natural and mechanical ventilation. In case of mechanical ventilation, the required ventilation volume flow rates were exported for energy simulation. Third, the results of IDA ICE were imported into the TRNSYS software, for the simulation of influence of AHU operational regimes.

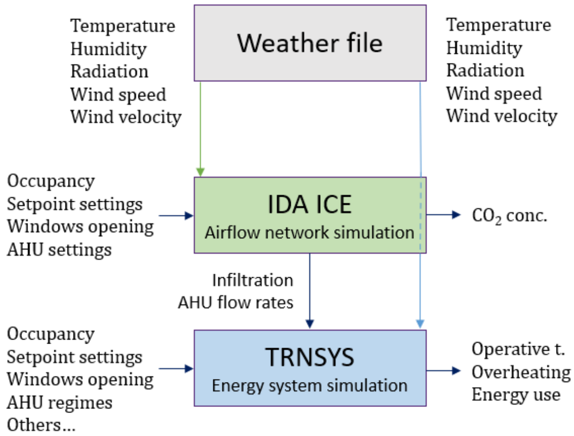

Fig. 1 – Combined simulation approach

Eleven scenarios combining various building model configurations and control strategies were simulated, as described in Tab 1. The building was simulated in two pre-renovation (Pre) scenarios and nine post-renovation (Post) scenarios, with the following ventilation strategies:

- Ventilation only by infiltration and opening of windows at night;
- Occupancy controlled ventilation; i.e. required fresh air delivery according to occupancy (following current standards);
- CO_2 controlled ventilation with the limit of 1,000 ppm (following the Pettenkofer criteria);
- CO_2 controlled ventilation with the limit of 1,000 ppm; AHU running in AC mode, that is, full

Tab. 1 – Simulated Scenarios

Nr.	Scenario	Ventilation strategy
1	Pre – realistic	infiltration and opening of windows at night
2	Pre – hypothetical	occupancy required fresh air delivery
3	Post – no AHU	Infiltration and opening of windows at night
4	Post – passive HX	occupancy req. fresh air delivery, without active heat exchanger
5	Post – active	occupancy req. fresh air delivery
6	Post – active	occupancy req. fresh air delivery, AC mode during overheating hours
7	Post – active	occupancy req. fresh air delivery, AC mode during overheating hours, night cooling mode
8	Post – passive HX	CO_2 controlled ventilation, without active heat exchanger
9	Post – active	CO_2 controlled ventilation
10	Post – active	CO_2 controlled ventilation, AC mode during overheating hours
11	Post – active	CO_2 controlled ventilation, AC mode during overheating hours, night cooling mode

power during overheating hours.
- CO_2 controlled ventilation with the limit of 1,000 ppm; AHU running in AC mode and overnight cooling mode with partial load for noise reduction.

The post-renovation scenarios targeted various operating modes of the AHU. In the scenario 3 the unit was disabled and in the scenarios 4 and 8 the active heat exchanger was not used. In the scenarios 6 and 10, the unit was running in AC mode, i.e., with full possible cooling capacity during the overheating hours. In the scenarios 7 and 11 the night cooling mode was enabled and the AHU ran continuously to pre-cool the dwelling overnight. The ventilation flow rate was limited to 30 % during the night, in order to reduce the noise emission. The cooling power of the AHU was not adjusted.

3. Façade-integrated air handling unit

To provide mechanical ventilation for the building after renovation, each dwelling will be served by the compact ventilation unit integrated into the prefabricated façade module as an inbuilt system. Unlike conventional local ventilation units designed solely for ventilation, the developed AHU has a two-stage heat recovery (active and passive). Aside of the passive and active heat exchangers, the unit is equipped with a controlled bypass system, filtration, and supply and exhaust fans, see Fig. 2.

The main innovation is an active heat exchanger, that consists of an array of thermoelectric elements providing both cooling and heating capability. The use of the thermoelectric element has several advantages such as (i) compact size, (ii) no mechanical parts, (iii) reliability due to the absence of liquid refrigerant circuit, i.e., without risk of leakage and related low maintenance requirements (iv) direct current device suitable for energy supply from PV panels and (v) universal application, where the same device can be used for heating and cooling purpose by reversing the current polarity. The main disadvantages are lower efficiency and limited temperature drop in comparison to refrigerant based solutions [4].

A numerical model of the initial prototype design of the unit was prepared in the TRNSYS simulation software. This sub-model representing the AHU was integrated to the TRNSYS model of the Terrassa building. The cooling and heating power of the active heat exchanger depends on the electric current and the temperature difference between the supply and exhaust air. It was modelled with the use of a performance map, which was prepared according to the characteristics of the installed thermoelectric cells.

The maximum volume flow rate of the ventilation air through the AHU is 150 m^3/h. The maximum heating power of each unit is 340 W, with COP approx. 2.5. The maximum cooling power is 250 W with EER approx. 0.65.

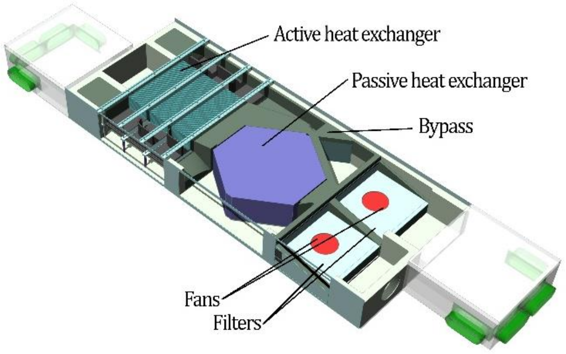

Fig. 2 – Integrated air handling unit

4. Real-Case scenario of Terrassa building Spain

One of the PLURAL targets is to install the developed PnU façade modules during a real demo site renovation and test them under real conditions. As a demo site for the presented type of the PnU façade module was selected the Terrassa building, located in Terrassa, Barcelona, Spain; i.e., a typical Spanish multi-family block of flats, see Fig. 3 and Fig. 4. The same building was considered for the numerical study.

This four-storey building with a basement used as car parking was completed in 2008 and consists of 18 existing dwellings; 6 dwelling per floor, while levels 3 and 4 are connected by 6 double-storey flats with underroof zones. The total area of the building is 1,280 m^2. The east façade faces the street, the west façade faces an inner courtyard. The longitudinal axis of the building is oriented 9° east.

According to the Spanish Energy Performance regulation, the building reached label D for CO_2 emissions and label E for primary non-renewable energy consumption. Thus, it is a good candidate for renovation with the use of PLURAL technologies.

Fig. 3 – Terrassa building demo site, aerial view

Fig. 4 – Terrassa building demo site, east façade

The 3D model of the building was prepared in the SketchUp geometry modeller. The model follows the real building topology, i.e., four storeys with 18 dwellings and a basement. However, the internal arrangement of the building was adjusted in the model, in order to simplify it. Zones with similar characteristics were merged (i.e., rooms within one dwelling, divided building corridors, etc.), resulting in the total number of 39 simulated zones.

Two representative dwellings were modelled and simulated in detail (including subdivisions into individual rooms), while the surrounding zones acted as boundary conditions. These two dwellings were significant in terms of boundary conditions and the results of their simulation could be extrapolated to the rest of the PLURAL affected building spaces. Both dwellings are located at the first floor; the first one faces the courtyard (ZA1-court), while the other faces the street (ZA1-street), see Fig. 5. The purple colour indicates either external solar shading volumes representing surrounding buildings in the model or adiabatic boundary conditions.

The building model for the TRNSYS software was prepared with the use of the TRNSYS Type 56. The location was considered identical to the real demo site, and the weather file used for the simulations was Meteonorm Terrassa TMY-2. Only the aforementioned dwellings were modelled in the IDA ICE environment.

The model was prepared in two configurations: pre-renovation and post-renovation, after the installation of the PLURAL PnU façade modules, i.e., with additional thermal insulation, new windows, building integrated PV system and façade integrated AHUs. For the pre-renovation building envelope characteristics, see Tab. 2. In the Tab. 3 are shown differences due to the renovation. The infiltration Equivalent Leakage Area (ELA) [5] has been calculated according to the Spanish regulation for residential buildings [6]. In addition to infiltration, the windows opening schedule was considered during the occupancy, where the opening ratio was determined with respect to outdoor temperature.

3.1 Configuration of the building model

For all simulated scenarios, identical profiles of occupancy, exhaust ventilation, internal heat gains, and basic dwelling technical systems were considered, see below. However, the ventilation control strategies differ, as described in Chapter 2.

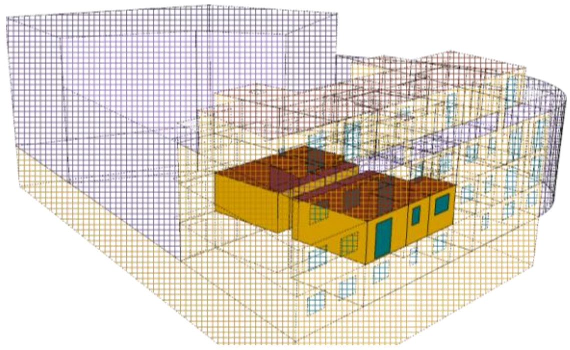

Fig. 5 – Building model, representative dwelling

Tab. 2 – Pre-renovation building envelope

Construction	Characteristics
Ceiling	0.37 $W/m^2{\cdot}K$
Floor	0.43 $W/m^2{\cdot}K$
External wall	0.49 $W/m^2{\cdot}K$
Partition Wall	0.69 $W/m^2{\cdot}K$ (between buildings)
Internal wall	1.81 $W/m^2{\cdot}K$ (between flats)
	1.71 $W/m^2{\cdot}K$ (towards corridor)
Glazing	2.72 $W/m^2{\cdot}K$, G-Value 50 %
Window frame	2.27 $W/m^2{\cdot}K$, 20 % frame area
Window blinds	0.66 $W/m^2{\cdot}K$, 0 - 100% opening
ELA	500 cm^2

Tab. 3 – Post-renovation building envelope (changes)

Construction	Characteristics
External wall	0.20 $W/m^2{\cdot}K$
Glazing	1.00 $W/m^2{\cdot}K$, G-Value 53 %
Window frame	2.27 $W/m^2{\cdot}K$, 20 % frame area
Window blinds	0.66 $W/m^2{\cdot}K$, 30 - 60% opening
ELA	200 cm2

Occupancy profiles

The occupancy profiles follow the realistic behaviour of the inhabitants, with respect to three different zone types in the simulated dwellings: common area, bedroom and bathroom; see Tab. 4. The profiles are related to the total number of occupants in each dwelling, while three people are considered in each of the two representative dwellings.

Tab. 4 – Occupancy profiles for different zones

Zone type	Occupancy
Bathroom	100 % at 7-8 h; 14-15 h; 22-23 h
Bedroom	100 % at 23-7 h
Common area	30 % at 7-10 h and 14-17 h 80 % at 17-23 h

Internal gains

Three types of internal heat gains were defined in the model: lighting, appliances and occupants. The heat gains were related to the floor area of the particular zone. The heat gain from occupants was calculated according to the occupancy schedule in each zone and considered as 2.15 W/m² [7]. Tab. 5 shows the internal gains from the lighting and white appliances, with respect to the zone type.

Tab. 5 – Internal heat gains schedule

Zone type	Occupancy
Lighting (common area)	0.1 W/m² at 7-18 h 0.5 W/m² at 18-19 h 0.8 W/m² at 19-23 h
Lighting (bedroom)	0.5 W/m² at 7-8 h 0.5 W/m² at 17-23 h
Appliances (common area)	0.03 W/m² at 22-8 h and 9-20 h 0.08 W/m² at 8-9 h and 21-22 h 0.2 W/m² at 20-21 h

Exhaust ventilation

Forced exhaust ventilation was considered in the open kitchen areas of the dwellings and in the bathrooms with total flow rate of 125 m³/h. It was operated during the following periods: 7-8 h at 50 %, and 20-21 h at 100 %. The exhaust ventilation is part of the air-flow network calculation, thus during these periods the total infiltration is increased (similar to the windows opening schedule).

Dwelling technical systems

A standard electric heating by electrical radiators was used in the simulated dwellings. The heating power was limited to 5.6 kW, corresponding to the real systems installed in the building. The heating setpoint was set to 21 °C between 7-10 h and 17-23 h. During the remaining time, the heating was operating with lower setpoint of 18 °C. There was no cooling considered, aside the cooling of ventilation air provided by the AHU's active heat exchanger.

The domestic hot water was prepared in electric tank heater with a volume of 80 l and 1.5 kW power. Daily hot water consumption in each dwelling with 3 occupants was considered 122 l.

Photovoltaic systems (post-renovation only)

A building integrated photovoltaic system was used in the post-renovation scenarios. The areas of 80 m² on the roof (inclination of 17°) and 100 m² on the east facade (inclination of 90°) of ONYX GL.01.MONO panels with 15% efficiency were considered. The produced energy was evenly divided among the dwellings with respect to their floor area.

5. Results of the simulation study

The main objective of the numerical study was to assess the benefit of PLURAL façade kits and to estimate the performance of the façade integrated AHU under different conditions. Indoor environment quality and energy consumption were evaluated and compared for 11 simulated scenarios. The realistic pre-renovation scenario (scenario nr. 1) was considered as a baseline for the comparison, as it represents the current conditions of the Terrassa building.

5.1 Indoor environment quality

Fig. 6 and Fig. 7 show the IAQ and operative temperature, respectively. The results are displayed for the dwelling ZA1-street and for the most relevant scenarios, for the sake of simplicity. The ZA1-street dwelling is the one more exposed to direct sun radiation and therefore the one more susceptible to overheating. It represents the more unfavourable case of the two representative dwellings. The figures show yearly conditions and conditions during four extreme days. Red dashed lines indicate the CO_2 concentration limit of 1,500 ppm (in Fig. 6) and the operative temperature limit of 27 °C (in Fig. 7).

From Fig. 6 it is apparent that the CO_2 concentrations in the two scenarios without controlled ventilation exceed the hygienic limit – in baseline scenario nr. 1 for approx. 11% of the occupied time and in scenario nr. 3 for 23%. This happens especially during the winter season, when ventilation by opening of windows is restricted due to the low outdoor temperatures. The maximum concentration of CO_2 exceeds 3,000 ppm in the baseline scenario and 4,400 ppm in the scenario 3, after the renovation of the building envelope, without the AHU. These concentrations are more than twice higher than the recommended limit for a good indoor environment.

The IAQ for all scenarios with AHU is sufficient throughout the year. The graph of CO_2 concentration during the extreme period of the year shows the differences in operation of AHU with various ventilation control strategies. CO_2 controlled ventilation (here scenario nr. 8) generally leads to higher concentrations in the dwelling, reaching the limit of 1,000 ppm. In such case, the ventilation volume flow rate is lower, which may lead to better energy efficiency, as discussed in the next chapter.

In all the scenarios, the operative temperature in the dwelling frequently exceeds 27 °C during the summer season, see Fig. 7. The graph for the extreme period (on the right) shows that the renovation of the building envelope with additional ventilation to meet the required fresh air delivery can lead to operative temperatures over 30 °C, if not done properly. This risk of overheating was mitigated by AHU temperature conditioning of the fresh air and an

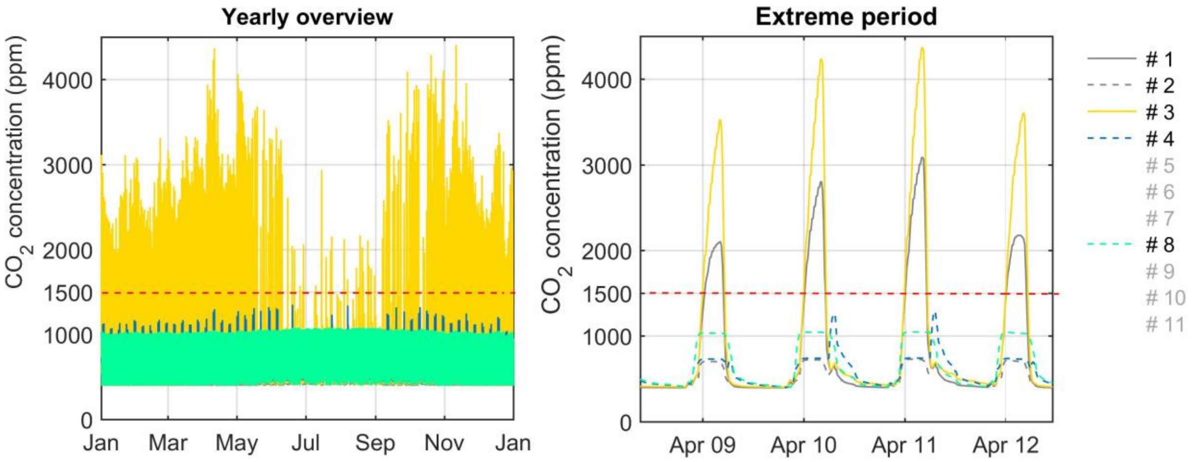

Fig. 6 – IAQ (represented by CO_2 concentration), dwelling ZA1-street, bedroom; red dashed lines indicated CO_2 limit

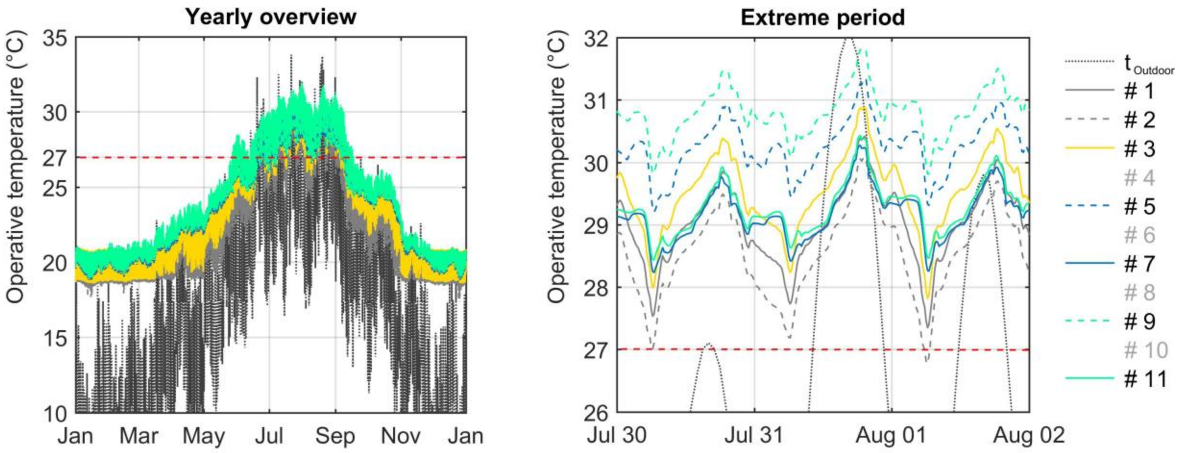

Fig. 7 – Indoor operative temperature, dwelling ZA1-street, average temperatures in the dwelling; red dashed lines indicate indoor operative temperature limit

appropriate ventilation control strategy. From the compared PLURAL scenarios, the lowest indoor temperatures were achieved in scenarios 7 and 11, when the AHU operated in AC mode, with overnight pre-cooling. Although the temperatures were slightly higher than in the baseline case (scenario nr. 1), the indoor CO_2 concentration was much better.

The indoor environment quality in both representative dwellings (ZA1-street and ZA1-court) was evaluated in Fig. 8 in the form of annual discomfort hours (overheating and IAQ – left axis) and annual discomfort degree-hours (right axis). It is evident that the pre-renovation conditions (scenario nr. 1) are not optimal. With ventilation only by infiltration and opening of windows, the CO_2 concentration frequently exceeds the desired limit of 1,500 ppm (for more than 660 hours per year). The additional ventilation flow rates must be delivered to satisfy the hygiene standards of IAQ. Scenario nr. 2 represents the situation prior renovation, when the required airflow is delivered via infiltration and represent secondary baseline for energy calculation.

The PLURAL renovation solution by the PnU façade modules was tested in the other 9 scenarios. Scenario nr. 3 (new windows, thermal insulation of the building envelope and PVs, without local AHU) leads to a significant increase in the number of discomfort hours with CO_2 concentration exceeding 1,500 ppm (for nearly 1,300 hours per year). This is due to the increased airtightness of the building envelope. The results of the study indicate that integrated AHU should be used as a part of the PLURAL solution, to maintain hygienic IAQ with desirable CO_2 concentrations.

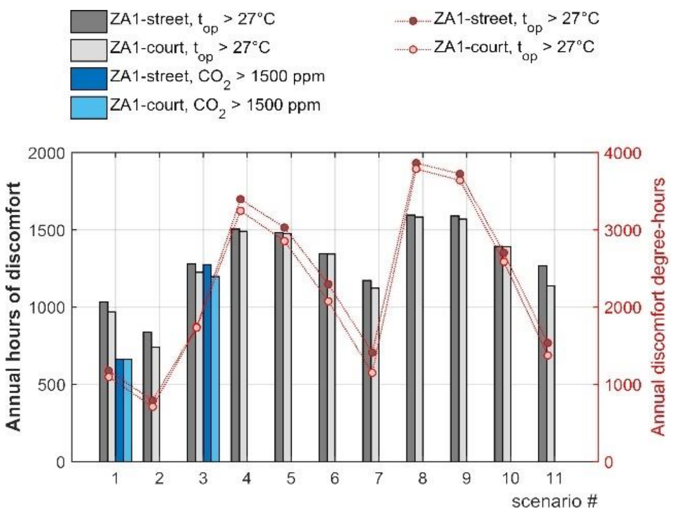

Fig. 8 – Indoor environment quality

All scenarios with the AHU (nr. 4 to nr. 11) show that, with controlled ventilation, the CO_2 concentration does not exceed the desired limit. However, ventilation by warm outdoor air results in the increase in the number of hours with indoor operative temperature exceeding 27 °C, as well as related number of the annual discomfort degree-hours. This negative effect can be addressed by cooling of the delivered fresh air and suitable ventilation control strategy. The best post-renovation environment quality was achieved in two scenarios with AHU operating in AC mode during overheating hours and providing night cooling. The best scenario was nr. 7 with the occupancy controlled ventilation, followed by the scenario nr. 11 with the CO_2 controlled ventilation. However, in both scenarios the number of overheating hours was still over 1,000, as the AHU is designed mainly for ventilation, with additional ability to condition the temperature of the delivered fresh air, rather than an actual air-conditioning device. Therefore, its cooling power is not sufficient to cool the whole dwelling.

5.2 Energy consumption

The energy consumption of the dwelling ZA1-street was evaluated in the form of total electricity use and total primary energy consumption related to the floor area of the dwelling. Results from all simulated scenarios are summarized in Fig. 9.

At first, it was checked that the distribution of the consumption among the building systems in the pre-renovation scenario (nr. 1) corresponds to the common situation in Spanish dwellings of a similar type [8]. This indicated that the building model was set in a reasonable way.

The comparison of energy consumption of the post-renovation scenarios clearly demonstrates the contribution of the PLURAL solution to the energy savings. The reduction of the total energy use was from 13 to 37 %, depending on the ventilation control strategy. The reduction of the total primary energy consumption was in the range of 34 to 59 %, considering building integrated photovoltaic system. Scenario nr. 11 (that is, CO_2 controlled ventilation and AHU running in AC mode during overheating hours, with night cooling mode) can be advised as the most favourable, with the best indoor environment quality, as discussed in the previous chapter, 17% reduction of total electricity use and 38% reduction of the total primary energy consumption.

5.3 Building integrated PV system

For all the scenarios with building integrated PV system, the self-sufficiency (demand coverage by PV production) and self-consumption (PV production matching) ratios were evaluated, see Tab. 6. While the self-sufficiency ratio is around 0.2 in all the

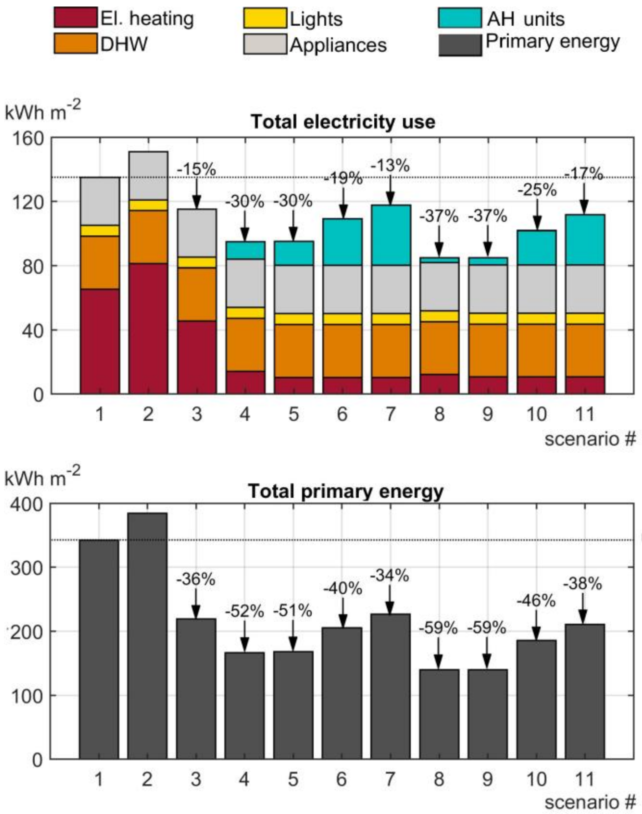

Fig. 9 – Energy consumption

scenarios, the self-consumption differs significantly. The scenarios with the AHU running in AC mode (scenarios nr. 6, 7, 10 and 11) indicate the best on-site matching of the electric energy delivery from the PV system with the energy demand of the building systems. The self-consumption ratios are 0.78 for scenarios 6 and 7 and 0.75 for scenarios 10 and 11. The high values are reached due to the AHU operating with the maximum cooling power during the hot periods of the day, when the intensity of solar radiation is usually high. This situation is the most favourable for the utilization of the PV generated electric energy.

Tab. 6 – PV electric energy indicators

Scenario	Self-sufficiency	Self-consumption
1	No PV	No PV
2	No PV	No PV
3	0.13	0.47
4	0.18	0.56
5	0.19	0.58
6	0.22	0.78
7	0.20	0.78
8	0.18	0.49
9	0.18	0.50
10	0.22	0.75
11	0.21	0.75

6. Conclusion

The paper demonstrates the risks related to the building envelope renovations aiming solely at better energy efficiency, i.e., increase of thermal insulation and change of windows, without considering proper ventilation strategy. It shows that such renovations may lead to overheating and unacceptable IAQ, with very high CO_2 concentrations. A new type of a façade module was introduced as a suitable solution that allows, in addition to increased insulation, the integration of other technologies such as photovoltaic panels and a controlled ventilation system. The integrated AHU provides the ability to condition the temperature of the air supplied for local ventilation of rooms by an active thermoelectric heat exchanger. The façade module is developed as a part of the Plug-and-Use concept within the H2020 project PLURAL and the simulation study helped the design team to better understand its performance during the yearly operation, before the manufacturing phase.

Combined simulation study with the use of IDA ICE and TRNSYS software was elaborated. Eleven scenarios of the Terrassa building Spain, real-case demo site for installation and testing of the developed façade module, were simulated. The building was simulated in two pre-renovation scenarios and nine post-renovation scenarios, with various ventilation control strategies. The integrated AHU was controlled according to the occupancy, CO_2 concentration, indoor air temperature (i.e., with cooling during overheating hours) and with over-night cooling mode. The main target was to predict the performance of the developed PLURAL systems. The indoor environment quality and energy indicators were evaluated.

It was demonstrated that without proper ventilation, the CO_2 concentration in the simulated dwellings exceeds the required limits, both in the pre-renovation case and in the post-renovation case without controlled ventilation system. The limit of 1,500 ppm was frequently exceeded especially during winter season, when ventilation by opening of windows is restricted due to the low outdoor temperature. The façade module with integrated AHU mitigates this risk and ensures good IAQ, with CO_2 concentration below 1,500 ppm thorough the year. However, in the summer season, the controlled ventilation by warm fresh air results in the increase in the number of hours with indoor operative temperature exceeding 27 °C. This negative effect was addressed by cooling of the delivered fresh air.

From the nine post-renovation scenarios, the one with ventilation flow rate controlled by CO_2 concentration indoors, AHU operating in AC mode, i.e., maximum cooling power during overheating hours, and with night cooling seems to be the most favourable. It indicates good IAQ during the year and one of the lowest numbers of overheating hours and related overheating degree-days. In this scenario, 17% electricity saving and 38% reduction of the primary energy consumption was achieved, in comparison with the baseline pre-renovation scenario. Also, the self-consumption ratio of the PV generated electric energy revealed the complementarity of the combined PV - AHU system, where the self-consumption was increased from approximately 0.50 to 0.75.

7. Acknowledgement

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