Building and Environment 208 (2022) 108585

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Building-integrated greenhouses raise energy co-benefits through active ventilation systems

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ARTICLE INFO

Keywords:
Urban agriculture
Industrial ecology
Circular economy
Energy efficiency
Rooftop greenhouses
HVAC systems

ABSTRACT

Buildings and greenhouses consume vast amounts of energy and natural resources for heating and ventilation. It is still unclear how the synergetic effect of combining greenhouses and buildings' forced waste airflows could improve both systems' energy efficiency. This study quantified the energy recovery potential of exchanging airflows in a rooftop greenhouse (iRTG) integrated with an office building HVAC system in a Mediterranean climate. Using monitored and calibrated energy model data, the results showed that the iRTG can act as a solar collector and as a sink for a building's low-grade waste heat. The magnitude of harvested thermal energy that could be recirculated into the building by the integrated HVAC system was 205.2 kWh/m^{2}y^{-1} and was limited by greenhouse low transmissivity (54%). The magnitude of building exhaust air was 198 kWh/m^{2}y^{-1} at temperatures sufficient to heat and cool the iRTG. Compared to a passive ventilated configuration, the integration of active ventilation strategies doubled the energy benefits. Building ventilation requirements directly determined building and greenhouse waste flows and energy benefits, which increased by 63.1% when air changes per hour moved from 1.59 to 3.16. Overall, this demonstrates that greenhouse and building functionalities could be coupled to contribute to urban circularity and sustainability.

1. Introduction

Environmental impacts associated with buildings are mainly due to their operational energy demand, which is estimated to be responsible for 40% of Europe's energy consumption and 36% of its greenhouse gas emissions [1]. The current EU building stock is very inefficient since more than 50% of it dates to pre-1970s [2]. This aging portfolio falls short of current thermal regulation benchmarks. Moreover, despite the EU's efforts over the last decade [3–5], only 0.8–1.2% of buildings are renovated per year [6], which is far from the 3% target set by the EU for 2030 [5]. A building's energy consumption is a complex function of its thermal envelope, which on average is around 180 kWh/m^2 and 250 kWh/m^2 for residential and non-residential buildings respectively [2].

Greenhouses occupy 3% of the EU's built-environment area [7,8] and during the 2009 to 2015 period it increased by nearly 40%, while the urban fabric footprint area increased 14% [7]. They are characterized by their translucent envelope needed to meet crops' natural light requirements, resulting in lower thermal envelope efficiency. As a result, their end-use energy demand ranges from 139 to 444 kWh/m^2 in southern Europe, around 400 kWh/m^2 in Eastern Europe and from 372 to 453 kWh/m^2 in Northern Europe, mainly depending on the greenhouse design and crop type [9]. Similar to buildings [10], life cycle assessment studies in greenhouses show that energy-related consumption for heating and forced ventilation systems are the main cause of environmental impacts [11–13]. This means greenhouses are today one of the most energy-demanding components of agricultural systems and

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https://doi.org/10.1016/j.buildenv.2021.108585
Received 15 August 2021; Received in revised form 25 October 2021; Accepted 12 November 2021
Available online 16 November 2021
0360-1323/

the European building stock.

Buildings and greenhouses are required to plan for a zero-emission, net-zero carbon future [5,14]. This is particularly challenging given the poorly insulated envelope of greenhouses and their low thermal mass. Both facts lead to higher energy demands in heated greenhouses that normally use energy from non-renewable sources. Research has attempted to provide reduced energy solutions for greenhouses for instance by improving solar gains (e.g. optimizing greenhouse orientation and covering materials) [15], increasing greenhouse thermal storage capacity, and minimizing energy losses by implementing passive strategies and energy-saving equipment. Results showed that in the Northern Hemisphere, E-W orientated greenhouses with an uneven-span shape and an insulated north wall are the most energy efficient. North walls are especially important as they can reduce greenhouse heating demand by 30% [16]. This is achieved using masonry or concrete-based materials, which increase greenhouse thermal storage due to their higher thermal transmittance (~0.9 W/m^2K) than most soils (which vary depending on their water content from 0.5 to 0.8 W/m^2K) [17].

Previous studies demonstrate that currently meeting greenhouse energy requirements with renewable energy (e.g. by means of photovoltaic or wind energy) is economically unfeasible [9]. Thus, one of the only current options could be the use of thermal energy coupled with heat storage [9]. Such an option could be further exploited with a closed greenhouse environment working as a solar energy harvesting system, as developed for Dutch greenhouses in the 1990s [18,19]. This can improve greenhouse energy efficiency by 50% [18], but it requires sophisticated energy recovery systems with underground (aquifer) seasonal storage. An alternative way to cover greenhouse heating needs is to exploit synergies between industrial systems by exchanging material and energy flows [20] to utilise low-grade heat flows. To this end, Sturm et al. [21] concluded that greenhouses are an ideal application for recovering industrial low-grade heat. This has already been tested in the industrial sector, for instance in France, to produce tomatoes year-round from household waste combustion using steam at 42 °C [22].

In this context, urban agriculture is emerging as an opportunity to introduce the circular economy in the urban environment within a multifunctional system that can provide and ensure local food production [23,24] and perform multiple societal and ecological functions [25]. Among these, greenhouses could serve as a way to improve building envelopes and mitigate some environmental impacts of building energy consumption [26–28]. In particular, Muñoz-Liesa et al. found that 4% of annual energy consumption is passively achieved via the four rooftop-integrated greenhouses in the ICTA building [28]. The energy benefits of building-integrated agriculture (BIA) are similar to conventional greenhouse optimization strategies [15] because (i) the host building's materials provide increased greenhouse thermal inertia; (ii) building inertia can exchange and store available solar energy; and (iii) the building's waste airflows are a source of low-grade heat to improve the greenhouse environment. These passive strategies demonstrated notable, quantifiable benefits for integrated greenhouses and their host buildings. They improved overall system-level energy efficiency without additional infrastructure or energy costs [28,29].

From a building perspective, HVAC systems consume around half of a building's energy [10,30,31]. This energy consumption could be significantly reduced if preheated or heated air from a greenhouse was used. Previous literature shows that greenhouses integrated with a building's HVAC systems can improve occupant thermal comfort, for instance by achieving constant day temperatures using preheated air from the greenhouse [32]. This could improve building insulation and inertia, and thus reduce a building's heating demand [33]. However, few cases have been quantified to date. In addition, air quality in buildings is increasingly gaining interest to prevent the entry of hazardous substances that can affect human health and the environment [34]. According to previous studies on the ICTA building [35], accumulated heat can be securely delivered to the building without posing health risks due to pollen concentration or plant pests. Hence, BIA boosts resource circularity between urban and agricultural systems by making the best use of the available resources to decrease integrated system resource needs.

This study quantified the energy benefits derived from active ventilation strategies applied to BIA. This was achieved by means of a building's HVAC systems, with the iRTG acting as a solar collector and a sink for building waste heat. Specifically, we aimed (i) to quantify a building's energy benefits from excess solar heating in an iRTG mechanically conveyed to preheat the building spaces below, in line with building ventilation needs; and (ii) to quantify greenhouse energy benefits derived from using available building exhaust air. The platform for this work was the Institute of Science and Technology (ICTA, Barcelona area), a research building with four integrated rooftop greenhouses (iRTGs) that are bidirectionally connected to a selected number of HVAC systems of offices and labs. After its commissioning in 2018, experimental tests during 2019 proved the feasibility of this symbiosis. This study extrapolates these test results to extended periods of time (2016–2018) and to the rest of ICTA building's HVAC systems that are not currently integrated with the iRTGs. The research was combined with modelling tools that were previously used to demonstrate energy benefits using passive strategies [30,32]. We therefore aim to further exploit these synergies and realize the full potential of active ventilation strategies applied to urban agriculture, to improve buildings' energy metabolism.

2. Methods

2.1. The ICTA building

The case study platform is the Institute of Environmental Science and Technology (ICTA) building. This building is in the Barcelona region, within the suburban area of the Autonomous University of Barcelona (UAB) campus. The building incorporates passive systems to reduce energy consumption and is designed to minimize resource consumption and reduce (and upcycle) waste. The building is integrated with four rooftop greenhouses (iRTGs), which are specifically designed to achieve this goal through the exchange of water, energy and CO_2 flows between the iRTGs and the building. Further information on greenhouse and building technical characteristics can be found in previous literature [36,37].

2.2. Building climate and control philosophy

The ICTA building has a 40 m × 40 m footprint and is 22-m high with 4 internal atriums. The building envelope is comprised of material with high solar transmittance values, which also covers the greenhouse structure and the double skin façade (Fig. 1). Internally, thermally isolated workspaces and laboratories are actively heated/cooled and placed close to the building perimeter and atriums, where they receive the greatest levels of daylight. These occupied zones are conditioned to have near constant temperatures, but the rest of the building (mostly transient spaces and corridors) are in free-float mode to reduce energy requirements. However, these free-floating zones are passively climatized and harvest residual energy from the conditioned spaces. Detailed information on the building climate controls can be found in Refs. [26–28].

2.3. ICTA-iRTG HVAC integration

Four rooftop greenhouses and a communal rooftop space have open airflow pathways (via atriums) with the rest of the building to enable the exchange of residual heat (RH) and CO_2. An integrated ventilation strategy ensures optimum exchange of airborne resources as follows:

1 Part of the Air Handling Units (AHUs, which are integrated in the building's HVAC system) from offices and laboratories are

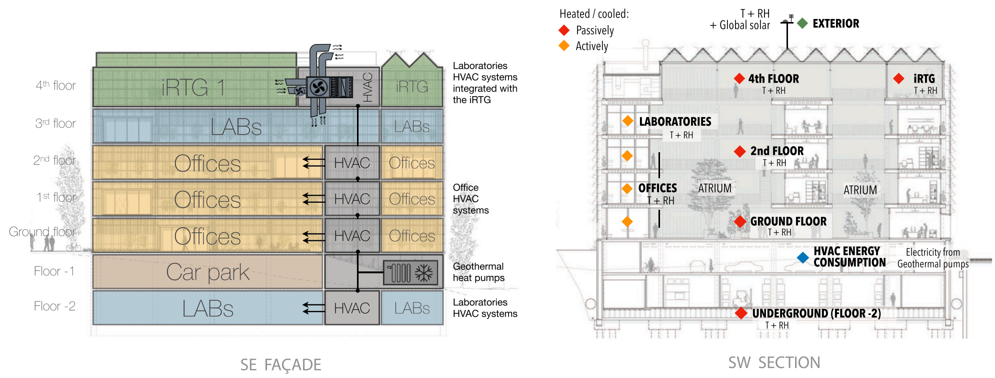

Fig. 1. ICTA building SE and SW façade section with the main temperature and relative humidity sensors (T + RH) in the building's active and passive heated/cooled areas.

bidirectionally connected to iRTGs by means of inlet and outlet ductworks (Fig. 2).

2 Four AHUs deliver unidirectional airflows from labs to iRTGs. The airflow rate for these units is designed to deliver up to 11,000 m^3/h each to meet positive pressurization of +10 Pa for labs.

3 To ensure the concentration of airborne contaminants is not exceeded, fresh air is required permanently (24 h/day), which offers the possibility of discharging enthalpy and CO_2 rich exhaust air to iRTGs when it is not recirculated.

4 Three AHUs each deliver 2500 m^3/h of fresh but preheated air from iRTGs to offices located around ICTA atriums when overheating occurs and according to relative humidity setpoints. To facilitate this, an additional AHU installed between two iRTGs (in SE and SW orientations) is designed to deliver up to 8000 m^3/h (with 1.1 kW-rated fans) of greenhouse preheated air to feed the three office AHUs using a ∅500 mm air duct (Fig. 2). This means that intake air for the three aforementioned office AHUs can come from atrium/external air or from preheated iRTGs.

Such an integrated system enables (i) enthalpy and CO_2-rich exhaust air from building HVAC systems to be delivered to iRTGs instead of being discharged externally and (ii) fresh but preheated air in the iRTGs to be used as supply air for offices. This delivers additional annual energy savings and reduces running costs. Prior to the integration of iRTGs, exhaust air from lab AHUs could only be discharged to the exterior or atriums, as a way to recycle waste heat and use it to passively heat common areas. However, a new HVAC system layout was designed to improve the value of waste heat by using it in iRTGs and allowing iRTG spaces to function as inlet air into the AHUs that served offices. In addition, the smart building management system governs active ventilation strategies (AHUs and HVAC) and combines it with passive strategies when needed.

2.4. Quantifying energy flows

Real world and modelled data were combined to quantify sensible heat energy gains by exchanging airflows between iRTGs and their host building (Fig. 3) on an hourly basis. Recorded hourly temperature differences between iRTG and building zones (locations marked on Fig. 1) during the 2016–2018 period were combined with actual hourly ventilation needs.

This approach is considered since an integrated HVAC system bidirectionally connects iRTG and ICTA offices and labs. Where the ventilation rate and air temperature needed to be processed to derive equivalent sensible heat gains, Eq. (1) was used according to the psychometric properties of gas-vapor mixtures.

$$Q_{s,\,i}(\text{kWh} / m^3) = mc_p(t_{1,i} - t_{2,i}) \quad (1)$$

In this equation, the hourly sensible heat potential ($Q_{s,i}$, in kWh/m^3 of mechanically conveyed airflows) is equal to the product of a mass of 1 m^3 (m) and the specific heat capacity (c_p) of air at 20 °C and 1 atm [38], which are assumed to be constant for the range of temperatures assessed here. Variables t_1 and t_2 are the temperature differences between the exchanged airflows according to the unidirectional flows that are assessed. No thermal losses are considered between the airflow volumes that are exchanged, due to the proximity of all system components

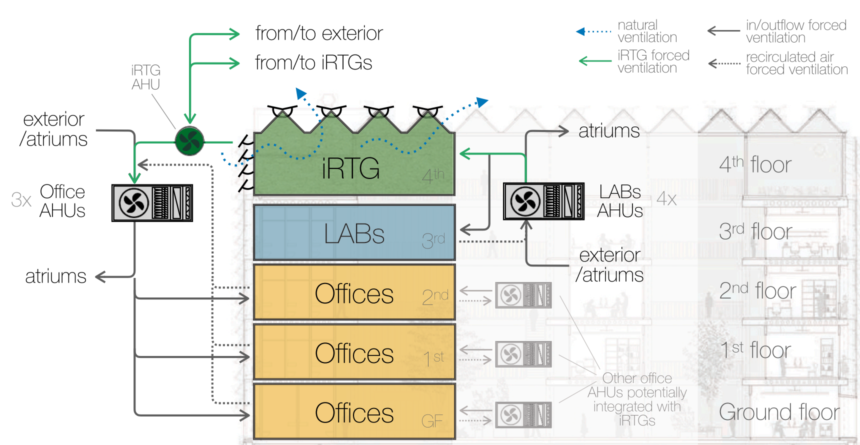

Fig. 2. Air Handling Units' (AHUs) airflow scheme showing the greenhouses' bidirectional integration with the ICTA building (laboratories and offices).

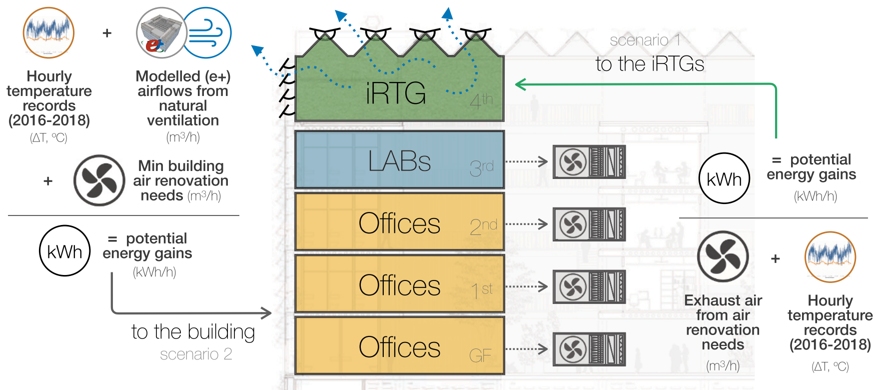

Fig. 3. Methodology to quantify total and potential energy gains to the iRTG and the building.

(AHUs, iRTGs, offices and laboratories spaces).

1 For unidirectional flows from lab/office exhaust air to iRTGs (via their AHUs), t_1 refers to lab/office and t_2 to iRTG temperatures.
2 For unidirectional energy flows from iRTGs to ICTA offices, thermal energies are calculated using the difference between iRTG air temperature (t_1) and atrium air temperature (t_2).
3 Since actual integrated AHUs in iRTGs retrieve air from third-floor atrium spaces, baseline temperature (t_2) corresponds to these recorded temperatures. For the rest of AHUs located on each office level that could be integrated with the iRTG, t_2 corresponds to the atrium air temperature of each corresponding level.

Equation (1) quantifies the sensible heat differences and ignores the difference in enthalpy resulting from air latent heat differences between both environments. This method was chosen due to the low relative humidity values found in the building and greenhouse environments (mainly at 40–50% [43]), which do not vary significantly. An in-depth analysis of the air state differences, including the latent heat differences, is available in the supplementary information and justifies this assumption. Apart from sensible heat differences, since greenhouse ventilation regimes require an additional AHU with a maximum fan duty of 1.1 kW_e to convey up to 8000 m^3/h using a 500 mm-diameter duct, the net energy gains (measured in kWh of electricity) can be calculated through Equation (2):

$$Q_{s,i\ ,\ net} = Q_{s,i} - E_{AHU,\ i} \cdot CoP = Q_{s,\ i} - \Delta t \cdot P_{AHU} \cdot CoP \tag{2}$$

where net sensible heat gains ($Q_{s,I,\ net}$, in kWh/m^3 of mechanically conveyed airflows) are calculated by translating the total electrical requirement of iRTG AHU ($E_{AHU,i}$, with $P_{AHU} = 1.1$ kW) across operating time Δt (in hours) into the equivalent sensible heat energy. This has been calculated considering the average coefficient of performance (CoP) of ICTA ground source heat pumps (GSHP), which is taken to be 3.5 for heating and 2.5 for cooling [28]. Pressure losses due to air friction were not calculated due to the proximity of all elements (<5 m). No additional energy expenditure was considered to result from air conveyed from the building to iRTGs, since this additional strategy does not result in lab AHUs spending more energy than in their normal operation (i.e., discharging exhaust air to atriums). Besides, no additional equipment (such as filters, dampers, coils, etc.) apart from existing components were considered, as current AHUs could provide the proposed bidirectional ventilation services from the iRTGs without posing a health problem [39].Finally, to quantify the annual total sensible heat gains (ΔH_s, n = 8760 h) derived from the calculated hourly net heating potential ($Q_{s,i,\ net}$), hourly airflow volumes (V_i) from the building spaces and the greenhouse need to be considered using Equation (3):

$$\Delta H_s(\mathrm{kWh}/m^2) = \frac{1}{A}\sum_{i=1}^{n} Q_{s,i,\ net} \cdot V_i \tag{3}$$

where A is the area of the heated greenhouses or offices that benefits from the heating flow. The hourly airflow volumes (Vi) are calculated from: (i) ASHRAE minimum fresh air ventilation needs (set at 1.59 ac/h for offices and 2.21 ac/h for laboratories, [38]) to determine the magnitude of thermal energy that is recyclable from the building to iRTGs and (ii) the minimum ventilation value between a building's fresh air ventilation needs and the natural ventilation flowrates that is needed to prevent overheating in iRTGs. The latter is derived from the calibrated EnergyPlus (E+) model previously used to study the natural energy flows of the ICTA-iRTG system [26–28]. By combing both values, the magnitude of iRTG to building energy recycling can be determined at times when this excess heat (normally discharged to the outside) can assist building heating loads by pre-heating parts of the minimum fresh air requirements of office and laboratories.

2.5. Mechanical ventilation philosophy

Hourly heat gains were calculated by imposing the conditions that need to be satisfied before residual air from one zone could be conveyed as input airflow to another. This was established after demonstrating the significant opportunities of exploiting sun peak hours' thermal mass and building waste flows during continuous tests across 2018. As previously mentioned, since relative humidity values in greenhouse and building environments are low, the ventilation philosophy is driven by sensible heat differences only, although the system can also operate according to a relative humidity threshold. Thus, based on these real case design strategies to optimize airflow thermal coupling, building exhaust air is conveyed to greenhouse spaces when:

i) Exhaust air from laboratories is available.
ii) iRTGs' temperature is below 22 °C, hence plants can benefit from additional heat input. Note that 26 °C is the upper bound of optimal iRTG temperature. However, air from the building zones does not reach this upper end.
iii) Lab temperature is higher/lower than outside temperature to allow iRTG heating/cooling as appropriate.

Similarly, greenhouse airflows are conveyed to office spaces when:

i) Office AHUs require outdoor fresh air.
ii) iRTG temperature is higher than the atrium and outside temperature.
iii) iRTG temperature has reached or exceeds 24 °C.

iv) Atrium temperatures are below 22 °C and hence can benefit from additional heat input.

Note that the approach here is to use greenhouse spaces only to preheat building ventilation requirements even though they could serve at higher rates as a heating source for the building.

2.6. Monitoring systems and modelling tools

The building managing system (BMS) is governed by Siemens Desigo™ Insight software (Siemens Building Technologies Ltd) using a Supervisory Control and Data Acquisition (SCADA) visual interface. The available actuators and sensors allow the system to make automated decisions based on user-defined variables and monitored building data. This system includes monitoring and operating controls to combine passive and active climate strategies, depending on a set of user-defined variables. A specially designed SCADA control panel integrates the above parameters and settings that turn on active and passive strategies in the greenhouse, enabling waste heat to be exchanged with the building and vice versa.

The available building temperature and relative humidity sensors and energy meters, solar radiation and wind velocity sensors used in this study are illustrated in Fig. 1. Hourly data generated by this monitoring infrastructure have been compiled in a Microsoft SQL database since June 2015. In addition, more than 100 sensors monitor the crop performance and iRTG variables such as temperature and internal solar radiation, to complement the Siemens SQL database. The same software holds (in a single database) the original recorded hourly values. After filtering and cleaning, they are aggregated into monthly intervals. Tableau Desktop software was used to import the building database from SQL files to detect and exclude possible errors in recorded values using the programming and visualization tools.

The data output was used to calibrate the E+ model using (i) the ICTA building's actual monthly energy consumption and (ii) the iRTGs' hourly air temperature and relative humidity (reported in details in earlier works [26–28]). This model used the user-defined inputs for active and passive spaces (e.g., temperature targets, ventilation regimes and occupancy) while the plant transpiration capacity of the greenhouse was modelled using the empirical formula of Bonachela et al. [40] for Mediterranean greenhouses, as described in Refs. [26–28]. Altogether, the output model met ASHRAE calibration limits against actual hourly data with respective MBE and CV (RMSE) values of +2.6% and +11.5% (air temperature) and +2.9% and 15.9% (relative humidity). The E+ model output results were combined with real data to examine the thermal performance of the ICTA building during 2016–2018. Former publications provide more information on modelling details and calibration rationale.

2.7. Energy scenarios

Buildings and greenhouses have different thermal requirements and, accordingly, different operating systems to satisfy specific missions. By examining energy and ventilation needs for all ICTA building zones and the iRTGs, different surplus energy flows were identified that could reduce overall resource requirements (Fig. 4). To realize this synergy, the greenhouse must be integrated with the building metabolism through (i) the physical connection of both systems (enabling the exchange of passive energy flows, which was already addressed in previous research [26–28]) and (ii) via active ventilation systems that can convey and recycle surplus energy between both systems. Three scenarios exist:

- Scenario 1 evaluates the heating and cooling energy potential of using building waste heat via the building's AHU system integrated into the greenhouse.
- Scenario 2 evaluates the heating potential to extract excess solar energy trapped in the greenhouse to heat the building using the existing building's AHU system integrated with the greenhouse.
- Scenario 3 expands the idea of scenarios 1 and 2 using unidirectional airflows from and to the greenhouse that can be exchanged with the underground floor that is thermally the most closely coupled zone with the substructure soil.

3. Results and discussion

3.1. Thermal effect on energy scenarios

A backdrop of ICTA-iRTG thermal performance is essential to contextualize the energy scenarios that were assessed. Recorded average dry bulb air temperatures of the main ICTA-iRTG actively and passively conditioned zones (Fig. 1) are presented for cold, temperate and warm months (Fig. 5). Cold months relate to December to March, warm months from June to September, and temperate months cover the rest of the year between both periods. In this study, the thermal exchange between ICTA and iRTG under a number of scenarios are added to findings reported in previous publications [28].

The ICTA building has an anchoring effect on the thermal behavior of the fourth floor that hosts four iRTGs as a result of:

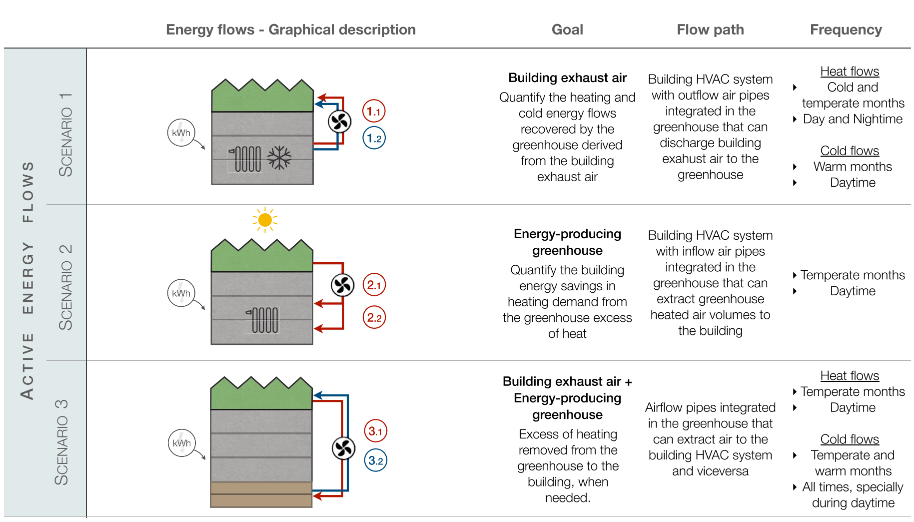

Fig. 4. Active energy recycling scenarios assessed.

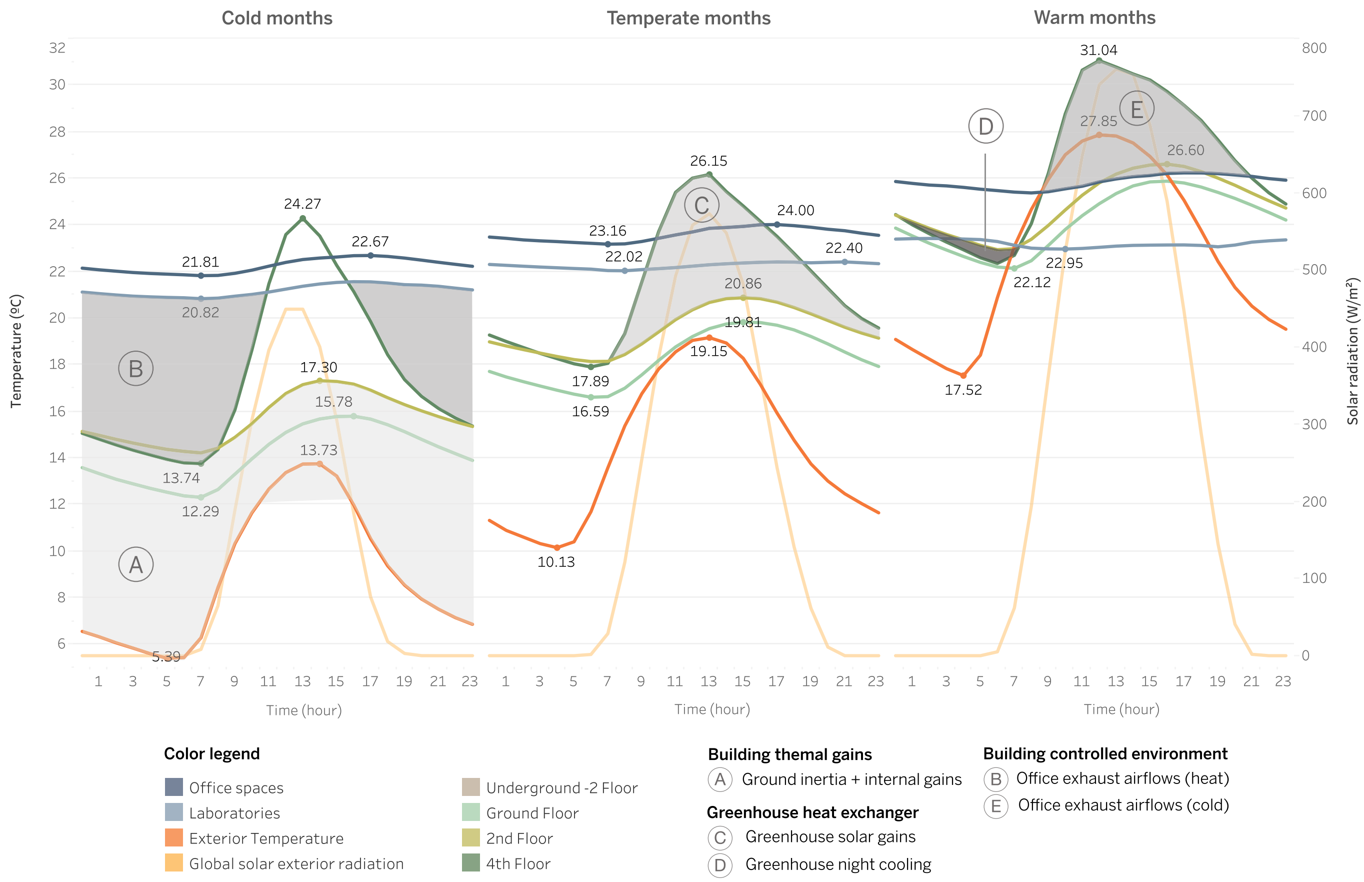

Fig. 5. Recorded average hourly temperatures of actively and passively conditioned ICTA-iRTG spaces and exterior solar radiation in cold (Dec–March), temperate (April–May, Oct–Nov) and warm months (June–Sep).

i) *Building thermal inertia* (captured in the grey area labelled [A] in Fig. 5): Ground temperature records for the −2 level show the great influence on the temperatures of the building's non-conditioned spaces (atrium ground and second floor). Temperatures are also affected by the building's internal gains and by the exterior weather temperatures (most notably in iRTGs). Fig. 5 shows how a 1 to 2-h delay exists between building and external air peak temperatures in cold months. This delay is interestingly increased to up to 4 h in warmer months, which highlights the value of building inertia in preventing overheating. Another valuable impact of building thermal inertia is the separation of peak external solar irradiance (just after solar noon) and peak internal temperatures (late afternoon), which assists with maintaining optimal plant growth condition in iRTGs and overheating prevention in offices.

ii) *Climate control in conditioned zones* (captured in the B & E area, supporting thermal exchange scenarios 1 and 3): This results from the ground heat inertia and building materials' heating inertia derived from internal gains. Building exhaust air conveys these energy gains to heat the iRTGs in cold months (area B) and cool them down when overheating occurs in warm months (area E).

iRTGs provide energy benefits for the ICTA building as a result of their capacity to operate as a dynamic heat exchanger by interacting with exterior climate conditions. This capacity is mainly exploited to deliver:

iii) Heating effect as a result of solar gains captured due to the greenhouse effect (Fig. 5, area C). Given that iRTGs are connected through openings to the ground and second floor areas, this impacts their temperatures.

iv) Cooling effect when iRTG automatic windows are opened during summer nighttimes, which induces strong thermal siphonage effects that counteract overheating and improve the building's indoor conditions (area D).

These three energy sources are not independent from each other and have a synergetic effect. For instance, solar energy stored in iRTGs' concrete slabs in the form of sensible heat directly affects building inertia and the climatized zones underneath iRTGs. By better integrating both systems, this synergetic effect allows energy consumption to be reduced by using the available thermal resources when and where needed.

3.2. Energy scenarios analysis

By calculating average monthly and hourly thermal differences, energy exchange potentials can be quantified accurately on a time-dependent basis. The time resolution is important to understand available thermal resources across the full annual cycle, which mainly varies as a function of available solar irradiance. In turn, it affects ambient temperature in iRTGs and building zones, and thereafter the opportunity for airflow exchanges to heat or cool both systems.

3.2.1. Scenario 1: Building exhaust air

The recorded average hourly temperatures in office and labs range from 21 to 25 °C (Fig. 5), which offers the possibility to heat or cool iRTGs over the year. Lab temperatures during colder months (December to March) at 19 h are on average 5.14 ± 1.96 °C above iRTG temperatures [28]. This offers significant temperature differences during nighttime and from 6 to 7 h, leading to potential thermal energy recovery per volume of delivered airflow at a rate of nearly 3 Wh/m^3 (scenario 1.1, Fig. 6). Since recorded average temperatures in labs are lower than in offices, potential gains are lower too (212.3 vs. 275.0 Wh/m^3). However, office spaces offer increased cooling potential during warmer months (95.1 Wh/m^3 annually). Maximum heating exchange potentials are reached at 11–12 h, also at a rate of nearly 3 Wh/m^{3}h. Another clear advantage of laboratories over offices is that they provide a constant exhaust airflow of 3835 m^3/h to the four iRTGs, even during unoccupied times (21–6 h, Fig. 6). This doubles the heating energy benefits (from 23.6 to 48.2 kWh/m^2) due to nighttime available airflows, of which 79.6% occur from November to March. In contrast, this favourable schedule for heat flows hardly infringes on cold flow opportunities that mainly occur in the daytime, which in total produce annual energy gains of 21.8 kWh/m^2. This cooling potential should be combined with natural ventilation to prevent overheating. Although the combination of passive and active ventilation strategies might decrease the quantified cooling potential, experimental tests showed better cooling capacity is achieved when active ventilation is used (i.e., lower greenhouse temperatures are achieved). Please see the supplementary information for further details.

Apart from the current integrated outflow ductwork from labs to iRTGs, AHUs from office atriums (located on the third floor) could easily discharge exhaust air to iRTGs. Office spaces also offer temperature differences that are 5.65 ± 2.49 °C warmer than iRTG at 19 h in colder months [28]. Since the temperature differences are higher, the hourly heating potential reaches more than 3 Wh/m^3 (Fig. 6). However, the available renovated air from office spaces guarantees a constant airflow only from 6 h to 21 h. At a rate of 3197 m^3/h, 26.1 kWh/m^2 of heat gains are available when office atriums' exhaust airflows are discharged into the iRTG (at instances when iRTG temperatures are below 22 °C). Similarly, cold energy flows show less cooling potential than lab exhaust air and amount to 9.1 kWh/m^2/year of energy gains mainly from May to September. When offices are occupied, building exhaust air could also be a source of CO_2 enrichment for plant growth [41].

Current infrastructure in the ICTA building could be largely improved if all offices were integrated with the greenhouse, allowing the upcycling of up to 11,625 m^3/h of exhaust air (and adding up to 15,460 m^3/h when combined with laboratories). Office spaces would offer fewer benefits than laboratories as they are designed to deliver air at a lower air rate to keep them at target temperatures and maintain proper air quality. However, integrating the exhaust air from all offices and laboratories would raise energy benefits from 26.1 to 143.3 kWh/m^2 (heating) and from 9.1 to 54.8 kWh/m^2 (cooling).

3.2.2. *Scenario 2: Energy-producing greenhouse*

This scenario explores the greenhouse as a solar collector to produce energy savings for the building by exploiting its greenhouse effect. The translucid envelope of iRTGs acts as a solar collector, limited by (i) available solar energy (greenhouse location); (ii) greenhouse covering material transmissivity (set at 83% at the beginning of its lifetime [42]); and (iii) greenhouse infrastructure transmissivity losses. All these limiting factors have seasonal variations as they rely on available solar energy and are modulated by the shadows produced by the greenhouse shading infrastructure. This directly affects the iRTG capacity to reach the 24°C-imposed maximum condition to use iRTGs' preheated air in the building AHUs.

ICTA-modelled iRTG annual solar radiation gains of 890 kWh/m^2 (Fig. 7) represent a greenhouse global transmissivity of 54% compared

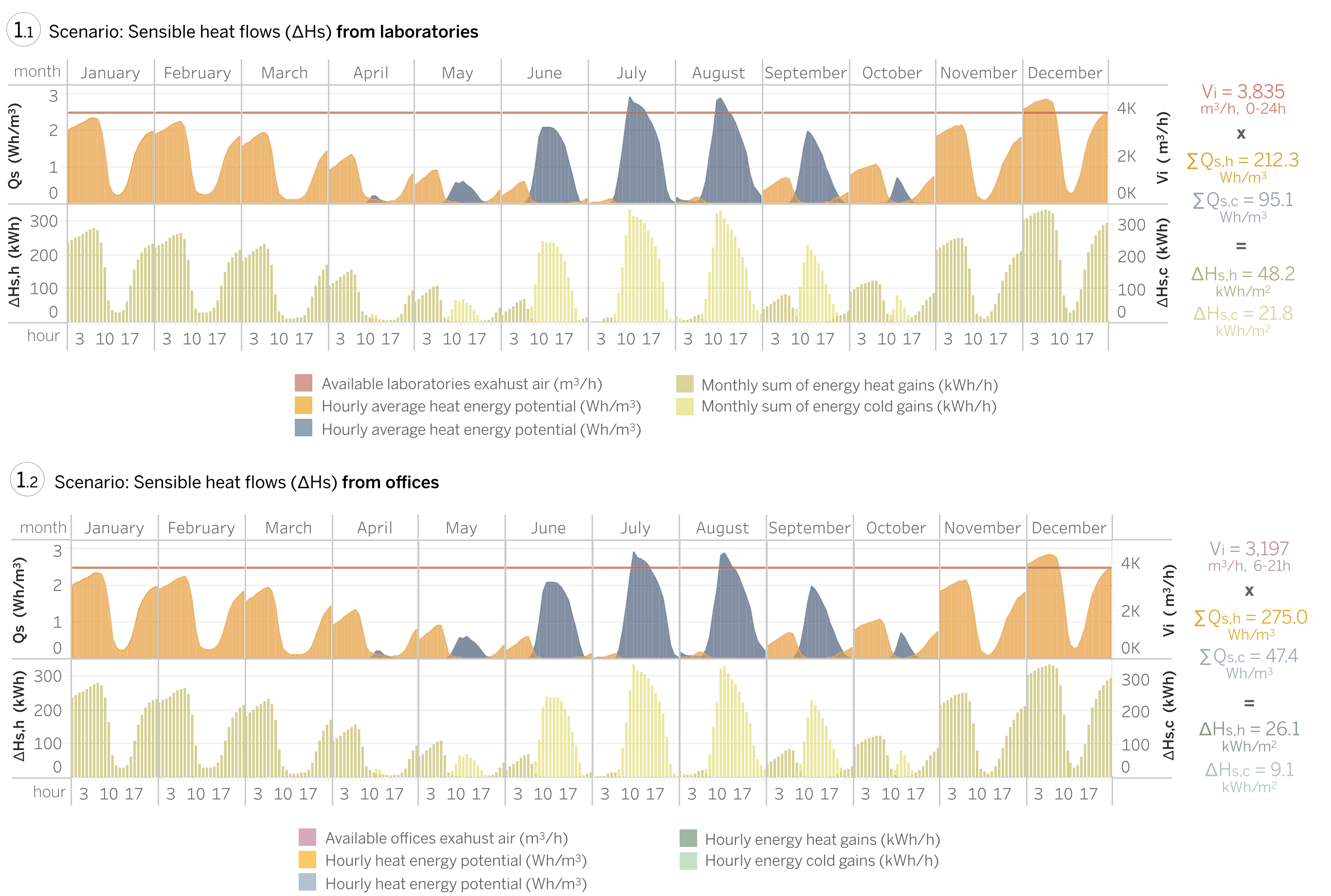

Fig. 6. Average hourly heating potential combined with the available exhaust airflow volumes from laboratories (S1.1) and offices (S1.2) resulting in iRTG sensible heat gains.

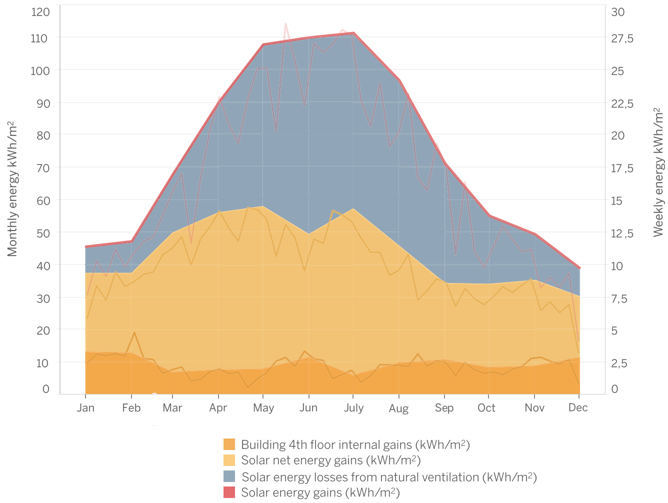

Fig. 7. Monthly and weekly average solar energy balance of iRTGs resulting from the E+ model.

with the average solar exterior radiation from the same period (2016–2018). This result is in line with actual recorded internal iRTG solar radiation (49–55%, depending on the season) [43], which is far from the most commonly reported greenhouse transmissivity values of around 70% [44]. This can be explained by internal shading caused by the iRTG curtains, shadings and airducts and the rooftop floorplan distribution, which creates opaque walls in two of the four iRTG façades. As a result, the urban environment presents greater obstacles to harvesting solar energy than open-field greenhouses [45]. This makes iRTGs more inefficient as solar collectors and growing systems when benchmarked against conventional greenhouses. It therefore imposes greater design considerations for urban greenhouses so that internal and external shadows can be minimized (ideally with improved material transmissivity and greenhouse design and orientation), which could maximize solar radiation gains. Otherwise, supplemental lighting should be considered, which in turn would increase crop yields [43] but also greatly increases greenhouse energy expenditure [46].

In addition, iRTGs' function as a solar collector is also influenced by the air dissipated through their automatic natural ventilation. Ventilation is an essential feature of greenhouses to prevent overheating during warmer months [44] enabling the release of surplus energy through automatic windows to keep daily temperatures at around 24–28 °C. Fig. 7 shows the monthly and weekly energy losses (kWh/m^2) resulted from iRTGs' natural ventilation and greenhouse infiltration produced by the calibrated energy model [26–28]. This illustrates the potential energy flows that could be used as an input airflow for AHUs via integrated and bidirectional HVAC in iRTG-ICTA, even during cold months (adding to around 9–10 kWh/m^2 monthly). Ventilation is usually needed in colder months as iRTG temperatures are on average 10.6 °C higher than the exterior temperature and thus normally exceed 24 °C during peak solar hours (Fig. 5). Greenhouse recorded temperatures exceed 21 °C during 73% of the annual daytime [28] because of the net modelled solar energy gains (30–60 kWh/m^2 monthly) with a minor contribution due to building internal gains (~9–10 kWh/m^2 monthly that is due to occupant, lighting and office equipment and is carried via ventilation air in building atriums (Fig. 7). Finally iRTGs offer a buffering effect that forms a passive dynamic insulation layer to the building with a net overall saving effect of 4% on building energy consumption [28].

Fig. 8 shows the greenhouse potential to heat the rest of the unheated spaces of the building (i.e., the ground and third floor, calculated from recorded temperature values) combined with the modelled greenhouse hourly natural ventilation needs (i.e., available airflows) and building air renovation needs. The latter include all potential integrated fresh air needs of offices and laboratories, as they are clearly exceeded by greenhouse ventilation needs. Thus, when fresh air ventilation needs to coincide with greenhouse ventilation needs, the excess heat can be conveyed to building AHUs, while appropriate greenhouse temperatures are ensured. This produces net energy gains that barely exceed 2 W/m^3, which are lower than scenario 1 as greenhouses are only passively heated. Moreover, electricity duties from additional fans needed to convey the excess heat reduces these potential thermal energy gains by around 20–26%. These occur when iRTGs require natural ventilation starting from 11 to 16 h in colder months, which in turn coincides with the overheating periods from the building's recorded temperatures.

Using this greenhouse preheated air (>24 °C) could reduce building heating loads by 33.7 and 52.2 kWh/m^2 annually for the offices on the third and ground floors, respectively. Maximum values are obtained in

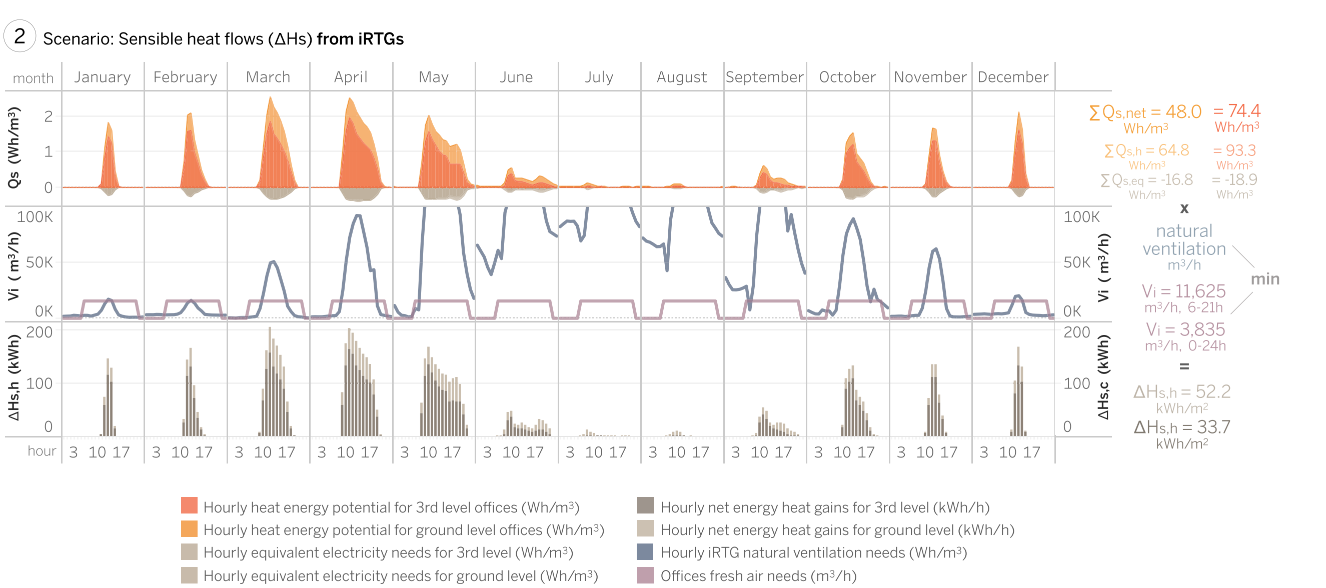

Fig. 8. Scenario 2: Average hourly heating potential coupled with modelled greenhouse natural ventilation and building required minimum fresh airflows. The resulting sensible energy flows recovered from the integrated greenhouse are shown for ground floor and third floor only, expressed in annual thermal energy saving per square meter of greenhouse (kWh/m^2·year).

April, when more heating potential and greater overlapping of greenhouse natural ventilation with building ventilation needs to occur. Similar to scenario 1, if all ICTA offices and laboratories were integrated, thermal energy benefits would rise to 205.2 kWh/m^2 annually.

Notably, preheated air from iRTGs could be used directly with minimum additional running costs in infrastructure and energy operation. According to Ercilla-Montserrat and collegues [39], the biological air quality of the ICTA's iRTG is adequate for recirculation without posing health risks to the building's users due to pollen concentrations or plant pests [39]. A further assessment of the heavy metal concentrations of this iRTG [35] showed air quality does not violate limiting factors, as it is below 50% of the limits established by the EU [34]. The preheated air from iRTGs could therefore be used directly with minimum additional running costs on infrastructure, filtering or efficiency penalties.

3.2.3. Scenario 3: Ground and below ground level air recycling

Thermally stable air from recorded ground and below ground levels can also be used as a bioclimatic strategy, as in nearly zero emission building designs, to preheat or precool the building air supplies and inner spaces [47]. By following the same approach as in the other scenarios, underground temperatures could be conveyed to cool the greenhouse and vice versa via the air ducts connected to and from the building's HVAC systems. However, additional infrastructure would be required to connect both levels. Thus, an in-depth analysis of the thermal and air-friction losses must be performed to accurately quantify this synergetic effect. Nevertheless, preliminary results show greater thermal energy potential than in scenario 2. This results in 157.2 and 305.8 kWh/m^3 of heating and cooling of annual gains, respectively (see the supplementary information for details and comparison with other scenarios). The reason for enhanced levels of energy upcycling here is the large temperature difference between the greenhouse during peak sunlight hours (i.e., when overheating occurs) and the relatively constant temperatures of sub-ground levels. The latter are influenced by thermal inertia, which boosts cooling energy all year as sub-ground zones have temperatures between 12 and 21 °C (Fig. 5) and high relative humidity, making it an ideal air source for greenhouse plant cultivation.

3.3. Ventilation-based energy benefits

The industrial symbiosis between greenhouses and buildings is based on available waste airflows from the building and iRTGs. Thus, ventilation needs are a key feature to quantify overall energy benefits.

i) Greenhouse perspective

Here, the ventilation needs are given by the EnergyPlus model outputs, according to greenhouse temperature setpoints. In turn, overheating needs are dependent on greenhouse location (i.e., latitude and longitude). Greater energy potentials could be obtained by lowering the ventilation setpoint temperature. This clearly results in a trade-off between greenhouse climate and building energy gains that could be further investigated. For instance, the extraction of excessive trapped solar energy from iRTG will negatively affect plant growth but could improve overall system benefits.

Together with temperature setpoints, forced ventilation might be required in certain climates or urban conditions to keep greenhouse relative humidity (RH) at 70–75%. Exceeding these values has been related to increased occurrence of plant disease, which has a negative impact on productivity [48]. It is therefore essential to include plant transpiration in building-integrated agriculture and energy models that capture RH changes in progressive stages of plant growth [49–52]. This could be important to determine greenhouse forced airflow needs, which, as discussed, will directly impact building and greenhouse symbiosis. An illustration of the need to prevent high RH values in greenhouses is the 2–3 ac/h of ventilation requirements, even during off-peak sun hours in wintertime, to maintain RH below a damaging level [53].

Here, no RH setpoints have been considered as iRTG humidity values range between 40 and 50% for low-bush plants and up to 67% for tomato crops [43]. Thus, natural ventilation ranges from 0.2 to 0.4 ac/h during the nighttime and colder months due to infiltration and rises to 3 ac/h when greenhouse overheating occurs. Wintertime excess RH buildup can sometimes require additional mechanical ventilation in BIA in certain locations [54]. If that were needed here to satisfy RH targets (e.g. at a rate of 2 ac/h), this would increase low-grade energy recovery from the greenhouse (below the 24 °C imposed condition). Minor differences might occur during temperate and warmer months, as natural ventilation exceeds building fresh air requirements. Modelling results show peak ventilation needs may be more than 30 ac/h, which falls within conventional greenhouse ventilation needs (30–60 ac/h, [55]).

ii) Building perspective

Fresh air needs of offices and laboratories are equivalent to 1.59 ac/h and 2.21 ac/h, respectively. These values depend on several factors including space use, occupancy density, and fresh air supply rates per person, and are set by international standards such as ASHRAE [38]. Thus, different ventilation needs might be required for the same building uses, as different criteria might apply. For instance, considering half the occupancy in our case study (from 0.250 to 0.125 p/m^2), air changes per hour would decrease to 0.95 ac/h. Similarly, higher ventilation rates are common in educational buildings, where the advantages of integrating a greenhouse have already been addressed [32,56]. In educational buildings, the occupancy density is higher (up to 0.65 p/m^2), which would increase air supplies at 3.16 ac/h. For these two cases, changing office ventilation requirements would influence the overall quantified benefits as shown in Table 1. Note that changing ventilation requirements allows an increase in the use of greenhouse-preheated air (Fig. 8) but also has a rebound effect on scenario 1, as more exhaust air would be available for iRTGs. Note that air changes per hour could be higher to compensate building infiltration (not accounted for here). This would reduce energy losses from inflow infiltration and even increase the energy benefits shown.

Thermal energy gains to the greenhouse from all potentially integrated offices and laboratories (scenario 1) decrease to 146.4 kWh/m^2·year for 0.95 ac/h (a decline of −26.1%) and increase to 323.5 kWh/m^2·year for 3.16 ac/h (a rise of +63.4%). In scenario 2, the increased benefit from greater ventilation needs shows that building air quality can be improved while heating energy is saved. To this effect, forced

Table 1
Sensible energy and equivalent electricity benefits in scenarios 1 and 2. *Note 2.21 ac/h are accounted for by laboratories, which were unchanged for all office ac/h options assessed here.

			Office air changes per hour (ac/h)		
Scenario	Energy source		0.95	1.59*	3.16
S1	Laboratories	ΔHs, heating		48.2	
		ΔHs, cooling		21.8	
	Offices (all)	ΔHs, heating	56.7	95.0	188.2
		ΔHs, cooling	19.6	32.9	65.2
	Labs + offices	ΔHs (kWh)	146.4	198.0	323.5
		Eq. Electricity (kWh)	46.6	62.8	102.4
S2	Offices (atria)	ΔHs, heating	20.7	33.7	58.9
	Labs + offices (rest)	ΔHs, heating	118.6	171.5	276.5
	Labs + offices	ΔHs (kWh)	139.3	205.2	335.3
		Eq. Electricity (kWh)	39.8	58.6	95.8
S1 + S2	**Sensible heat gains (kWh)**		**285.7**	**403.2**	**658.8**
	Equivalent electricity (kWh)		**86.4**	**121.5**	**198.2**

ventilation could be used as a heating source and maximize profits from greenhouse-heated flows. Finally, the overall equivalent electricity gains (under heating and cooling CoPs of 3.5 and 2.5) show similar trends in both scenarios, with an overall 28.9% decrease for 0.95 ac/h and 63.1% increase for 3.16 ac/h (Table 1).

The integration benefits for buildings and iRTG therefore exist for building types other than offices. By interconnecting other urban systems or subsystems that can offer higher values of airflows at elevated temperature or RH, greater benefits would be achieved. Like laboratories in the ICTA building, the feasibility of symbiosis with building-integrated greenhouses has already been shown for sport centers [24,33] or industrial buildings [22,57]. In particular, Thomas et al. achieved electricity gains of 178.4 kWh/m^2 by recovering waste hot water (42 °C) from industrial processes with a water-to-air heat pump (CoP 4.2) [57]. This value is higher than in the ICTA-iRTG case study, as waste airflows at 22–24 °C produced equivalent thermal upcycling gains of 62.8 kWh_{elec}/m^2 to the greenhouse (and up to 102.4 kWh_{elec}/m^2 with 3.16 ac/h, Table 1). This shows industrial symbiosis could be further exploited and made efficient using urban greenhouses, where the integrated greenhouse does not necessarily need to be placed on the rooftop but could be next to other buildings to facilitate energy exchange.

3.4. Strategies to recover energy flows

Exchanging building and greenhouse waste airflows is a very simple solution to use the energy stored in the systems and keep its value. It boosts energy symbiosis in both integrated systems: the total sensible heat gains achieved were 403.2 kWh/m^2 (with 1.59 and 2.21 ac/h), while 462 kWh/m^2 was previously obtained with passive strategies [26,28]. By using active strategies, building energy needs could be further reduced from 4% (passive scenarios only) to 12%, which is equivalent to nearly 50 MWh of annual electricity savings.

However, since air is the heating transport medium, its low thermal capacity and high ventilation rates require bigger air pipes than those used to connect iRTGs with the ICTA building (ø500 mm). This makes heat transport to other building locations more difficult than other heating storing media. Alternatively, an additional air-to-water heat exchanger could be employed, which would in turn increase the system complexity and may reduce its efficiency (note that energy efficiency ranges around 50%, i.e., large ventilation flows are required like those produced in the greenhouse). Other heat exchangers could be further studied and have been identified for ideal application in building-integrated greenhouses, as they can efficiently exchange very small temperature differences stored in the greenhouse [58].

To maximize energy benefits considering the air's low thermal capacity, a storing medium can be used to retain recovered energy from the greenhouse. In the Netherlands, closed controlled greenhouses employed air-to-water heat exchangers to transfer heat to underground aquifers for storageallowing an increase in energy benefits by means of seasonal storage [18,59]. Here, building materials and the greenhouses' concrete floors can function as an absorbing storage medium that passively heats the building and the greenhouses. The building's thermal inertia is essential in active and passive strategies as a storing media during the day that can naturally release heat during the night. The ICTA-iRTGs' microcement finishing of concrete floors enhances heat storage functions as no insulation or obstruction layer is placed between the thermal mass and the adjoining space. Other heat storage systems such as PCMs [60] or rock beds [47] could improve energy benefits within integrated systems.

4. Conclusions

Buildings and agriculture are two significant energy-intensive sectors globally that need to plan for carbon neutrality. This study examined the energy benefits of coupling these two sectors using building-integrated rooftop greenhouses as a case study. Experimental and modelling data demonstrated significant synergetic opportunities and a wide range of optimization challenges to exploit the systems' thermal mass and delayed peak temperatures across different zones. This necessitates a rigorous design stage strategy to optimize thermal and airflow coupling of multiple zones without creating unnecessary complexity.

From a greenhouse management perspective, the observed data showed urban greenhouses to be an ideal sink for a building's waste heat; with 198 kWh/m^2/year of thermal energy gains available from ICTA to assist its rooftop greenhouses' thermal and ventilation needs. This is due to wintertime air being warmer in offices and labs than in iRTGs (producing 143.3 kWh/m^2/year), while lower summertime cooling potentials exist (54.8 kWh/m^2/year). To further reduce greenhouse overheating, experimental tests highlighted the positive effects of employing passive and active ventilation.

The case study greenhouses harvested 890 kWh/m^2 of solar energy per year that were diverted to function as fresh air supplies to offices (requiring 1.59 ac/h). This resulted in 205.2 kWh/m^2/year of sensible heating gains to the building, limited by the low greenhouse solar transmissivity values (54%). Urban greenhouses should be designed to ensure maximum light transmissivity to improve their solar collector function. When building ventilation needs are higher (e.g., education facilities with 3.16 ac/h), the magnitude of potential solar energy recovery from iRTGs can rise 61.1% against an office space. Moreover, the excess iRTG solar energy can be exploited as a heating supply, while reducing building infiltration and improving indoor air quality.

In conclusion, building-integrated active ventilation systems can benefit from building assets to improve material and energy circularity, saving 8% of the building annual energy needs. This doubles (1.9 times) the heating energy benefits derived from passive strategies. Future assessments should investigate building thermal inertia to further improve energy storage capabilities. In turn, this demonstrates that BIA could add value to buildings, while creating green and resilient infrastructures in cities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to the Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement de la Generalitat de Catalunya (Catalonia) for the award of a research scholarship (FI-DGR 2020) to Joan Muñoz-Liesa. Authors also acknowledge financial support from the Secretaria d'Universitats i Recerca del Departament de Recerca i Universitats de la Generalitat de Catalunya for the grant awarded under AGAU 2020 PANDE 00021 and the Spanish Ministry of Science, Innovation and Universities, through the "María de Maeztu" program for Units of Excellence in R&D [CEX2019-000940-M]. This work was additionally enabled by the Càtedra JG Ingenieros – Universitat Politècnica de Catalunya and the UK Engineering and Physical Sciences Research Council grant EP/P001173/1. Authors are also grateful to Elisa López-Capel, Sostenipra research group and ICTA-UAB staff for the very valuable support, advice and help.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.108585.

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