Improving urban metabolism: Bi-directional energy and environmental benefits of rooftop greenhouse and building integration

Joan Muñoz-Liesa[1], Mohammad Royapoor[2], Elisa López-Capel[3], Eva Cuerva[4],
Santiago Gassó-Domingo[4], Alejandro Josa[1]

[1] Department of Civil and Environmental Engineering (DECA), School of Civil Engineering (Escola de Camins), Universitat Politècnica de Catalunya (UPC), Jordi Girona 1-3, Barcelona, Spain

[2] National Centre for Energy Systems Integration (CESI), Urban Sciences Building, Newcastle University, Newcastle upon Tyne, NE4 5TG, UK

[3] School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, UK

[4] Department of Project and Construction Engineering (EPC), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Edifici H, Av. Diagonal, 647, Barcelona, Spain

Abstract

Rapid global urbanisation in 21st century results in cities consuming vast resources but also offering unique opportunities for more integrated and circular resource management. This work investigates potential benefits of urban agriculture and buildings integration through a demonstrator building (ICTA).

Actual building and integrated Rooftop Greenhouse (iRTG) data demonstrate wide thermal profiles across ICTA six levels and the potential for heat exchange within the building. Calibrated model monthly results indicate reduced building heating needs resulting from iRTG inclusion. However, more modest GSHP electrical cooling reductions resulting from plant transpiration showed reversing potential which requires more in-depth analysis of underlying principles.

Introduction

The importance of reducing energy consumption in buildings and its corresponding environmental impacts are a top priority for international community and one of the main EU policy and research priorities. The building sector is the main user of the world's energy supply and in Europe is responsible for nearly 40% of the total energy usage and 36% of the carbon emissions (European Union 2010; Environment Programme 2007). This has resulted in a wide range of global initiatives to reduce building energy consumption that in Europe finds legal mandates in a range of directives designed to encourage member states to deliver carbon emission reductions and building energy efficiencies. Among others, the 2010 Energy Performance of Buildings Directive and the 2012 and 2018 Energy Efficiency Directive are the EU's main legislative instruments (European Union 2010); (European Union 2012); (European Union 2018)). Improving energy efficiency and performance in buildings are also notably important in reducing operational cost which in light of rapidly increasing energy prices are gaining greater momentum (European Political Strategy Center 2018). Different authors report according to (Popescu et al. 2012) that in Europe, energy-efficient saving measures in residential buildings have an increased willingness to pay economic value of 3% to 13% of the standard prize.

Increased urbanisation is another inevitable trend. According to United Nations, urban populations are projected increase from 30% in 1950 with projections of up to 68% by 2050 (Population Division 2018). For this reason, cities will continue putting more demand on resources that are often sourced from rural areas resulting in carbon-intensive transportation of goods as a side effect. The relationship between demand and supply of all type of resources require a more integrated approach, with potentially large benefits resulting from connecting independent production systems.

Similarly, the rising population and increasing value of land has moved agricultural systems away from city boundaries. Counter to this movement is the science and practice of urban agriculture that assesses the integration of civic life with different forms of urban agriculture; such as gardens and allotments, and in particular, in the form of building integrated rooftop greenhouses. Other integrated approaches have already been examined in logistic and industrial parks, whereby considerable potential was identified in recycling waste (or excess) heat for other industrial purposes of which greenhouses are one (Thomas et al. 2017). By the incorporation of urban agriculture into building form, additional efficiencies can be derived, where waste heat, humidity and occupant-generated CO_2 can be utilised to create ideal rooftop conditions for cultivation of plants and in doing so save the energy that would have originally been supplied via carbon intensive fossil-fuels (Nadal et al. 2017). Greenhouses are the dominant energy users of the energy inputs in the food production sector which account for between 13 and 15% of total energy usage in developed countries (Nadal et al. 2017; Wallgren & Höjer 2009). Moreover, this sector is expected to rise due to the increasing worldwide population by nearly 60% in 2050 (Population Division 2018). On the other hand, with proper design, operation and monitoring, greenhouses offer a more controlled environment and resilience to climate factors, enable suitable productivity and can prolong the growth season to full annual cycles. Thus, they have the potential to satisfy much of the growing demand (Piorr et al. 2018).

Considering the energy-intensive nature of both buildings and agriculture, the integrated rooftop greenhouse (iRTG)

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concept not only improves overall system energy efficiency but also brings freshness, locality and sovereignty into food production. It also creates building level amenity and education spaces to form greener and multifunctional cities that are more land- and resource-efficient.

The iRTG concept presented in this study is based on a real-world demonstration site where a 6-storey office building is fully integrated with an iRTG. Actual energy and environmental data across multiple annual cycles is available to assess the benefits of building integrated agriculture and also to calibrate an energy model which provides a set of initial winter and summer time energy related scenarios. Both actual and calibrated model data are used to examine the industrial symbiosis between building climate management and greenhouse microclimate systems. This outlines the benefits of a departure from a linear to a circular economy and in doing so meeting the growing social demand and possible resource-shortages.

This work presents preliminary results and method statement. Real monitored data from the building during 2016 and EnergyPlus^{TM} version 9.1 software simulation results are used to quantify the magnitude of excess energy that can be recirculated within both building and iRTG systems and improve energy efficiencies in both systems. In doing so, and when scaled up across multiple buildings to district and city scale, it would be possible to estimate the current and potential resources available in industrial systems or in cities (in terms of land use, sunlight spaces, water resources or waste heat) that can be profitable for other industrial systems.

Method

Case Study Building

ICTA-ICP building (abbreviated to ICTA) is a research, laboratory and teaching facility located in the Autonomous University of Barcelona (UAB; Bellaterra campus). The building comprises of 2 sub-ground levels (housing parking facilities and palaeontology storage) and 5 levels above the ground, with the fifth one housing four greenhouses (iRTGs) for food production (measuring 128 m^2 each, with currently only two in operation). This building has been the first real-world demonstrator in south Europe as a living lab that in addition to the office and lab space, provides a research platform for urban agriculture and building-greenhouse synergy. The building design incorporated a vast amount of recycled material, grey water recycling, underfloor and roof heating, displacement ventilation regime assisted by a double skin façade and internal atrium, and low carbon heating via geothermal heat pumps. A Supervisory Control and Data Acquisition (SCADA) intelligent building automation system enables on-going control adjustment to reflect changing requirements and experimental data collection.

The available operational data of the building from its inauguration in 2015 is used to assess real-world assessment of multiple iRTGs and thus, quantify waste energy flows, CO_2 and water symbioses of such demonstrators. Actual high-resolution data also enable the creation of building models to investigate several energy related alternative scenarios and possible implementation around the world.

Data backhaul and model calibration

In the past few years the availability of pervasive sensors and high-resolution energy consumption data has enabled the creation of high-fidelity energy models that can enable a range of energy and environmental analysis including advanced building control strategies (Royapoor et al. 2018), optimal retrofit solutions and fuel and fabric optimisation studies (Prada et al. 2018). It was demonstrated that a building energy model calibrated to satisfy the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guide 14 acceptance criteria could predict annual hourly space air temperatures with an accuracy of ±1.5 °C for 99.5% and an accuracy of ±1 °C for 93.2% of the time (Royapoor & Roskilly 2015).

In order to examine the bi-directional (from and to the greenhouse) energy benefits of an iRTG, both real data and calibrated model simulation outputs are required. The actual data is used to calibrate EnergyPlus model in order to produce later both energy and environmental results of the ICTA building with no iRTG and with the roof structure composition achieving a statutory U-Value of 0.41 W/m^{2}K according to the roof insulative requirements defined by the Spanish Technical Building Code for the Barcelona region CTE-DB-HE (Standard 2006). In order to fulfil these requirements, monthly energy consumption data is calibrated (see Figure 1) and used to evaluate the model energy prediction accuracy. These results shall satisfy ASHRAE Guideline 14-2014 (Guideline 2014).

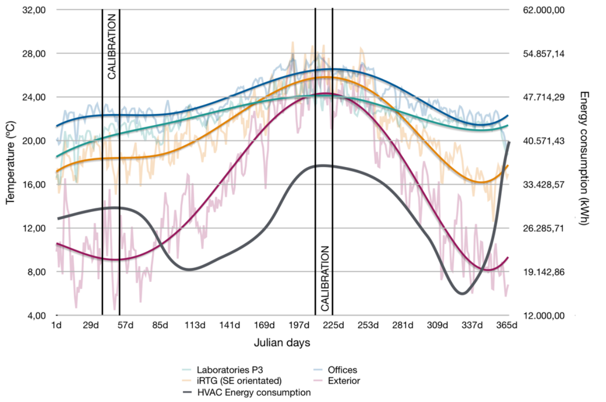


Figure 1: Calibration rational and annual 2016 data of the ICTA building energy consumption and temperatures

Control schedules and monitoring tools

There are different zones in the ICTA building defined by their usage and climatically controlled differently. Thus, 5 control schedules regulate their internal climate administering heating, cooling and window openings, defined by each type of internal climate as follows:

1. Workspaces and offices: 21-23-25ºC temperature target depending on the season (winter – intermediate – summer). Users from offices can regulate these temperatures ± 1.5º C.
2. Laboratories (Levels -2 and 4): 22º and 23ºC depending on the labs, with heating and cooling needs and continuous air extraction from 7:30h to 20:30h. Differential pressure of +10 Pa has to be maintained due to the laboratory equipment.
3. iRTGs (5th level): unheated / uncooled, only forced ventilation from level 4 laboratories. Temperatures vary depending on the season (from 13 to 32º C on average in 2016).
4. Common spaces: unheated / not cooled. Temperatures vary depending on the season (from 11 to 29º C on average in 2016).

The main building automation system responsible for the working modes, climate controls, windows schedules, etc is provided by Desigo™ Insight software (Siemens Building Technologies Ltd) integrated in a SCADA control panel. In excess of 2000 sensors and actuators operate the Siemens control system while 340 of these components produce hourly data that are recorded in a SQL database since building inauguration. All these tools are offered to the researchers in order to monitor, alter, check and control the operating system.

In addition to Siemens system, 85 sensors from a Campbell data acquisition complements the building data in the iRTGs and the exterior of the building to measure air temperature, humidity and global solar radiation every 5sec and record the averages at 10min intervals. Other logged parameters include air quality, pH and conductivity of irrigation water, soil moisture, etc. Figure 2 shows the sensors from both Siemens and Campbell systems that were used to report the results of this work.

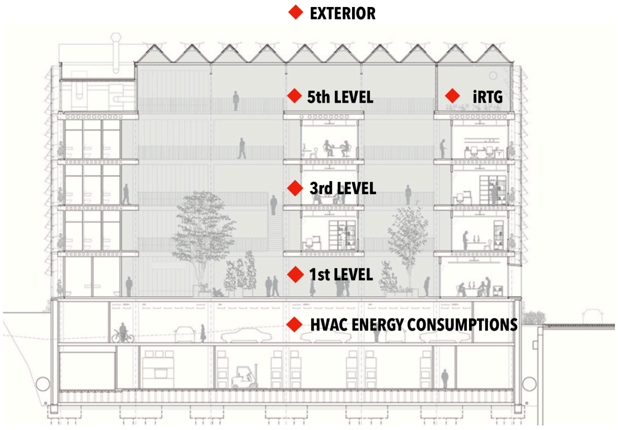


Figure 2: Plan of the ICTA sensors analysed

Building to greenhouse energy flows

The ICTA building, as a function of its thermal mass and climatically controlled environment has an anchoring effect on the iRTG. This overall thermal benefit was demonstrated to be equal to 341.93 kWh/m^2/yr in an earlier work (Nadal et al. 2017).

The thermal energy that migrates from the ICTA building to the greenhouse is mainly via natural and forced ventilation air. Air handling units (AHUs) plant duties, air flow volumes and discharge temperatures are used to quantify the amount of forced thermal energy (Q_f) that is injected into iRTG using formulae 1.

$$Q_f = mc_p(t_i - t_e) \tag{1}$$

Where m and c_p are the mass flow and specific heat capacities of air, and t_i and t_e are internal and external temperatures, respectively. Particularly, these energy flows have been quantified by calculating the difference between the hourly average temperature of the laboratories and the iRTG imposing restrictions of heat demand only when the following conditions are satisfied: (i) the iRTG is below 24ºC, according to the researchers experience and crops necessities; (ii) the lab temperature is lower than the external temperature (so there is no heat necessity).

Furthermore, the total ASHRAE Guide 14 considers a building model calibrated if monthly Mean Bias Error (MBE) values fall within ±5% and monthly Cumulative Variance of Round Mean Square Error (CV, RMSE) values fall below 15%. MBE and CV(RMSE) indices were deduced over monthly intervals in order to study variations in this timeframe too. MBE figures provide an indication of errors averaged to the mean of measured values but suffer from the cancellation effect.

Greenhouse to building energy flows

The addition of a rooftop greenhouse has the potential to be an insulating influence in winter months. In summer months and with a dense coverage of vegetation that create significant transpiration, a cooling effect can be ensured when compared to inactive roof surfaces that absorb and transmit the solar energy into the building envelope. The transpiration impact of the plants in this work is an experimental solar radiation-based model proposed by Bonachela et al. (2006) that uniquely represents Mediterranean greenhouses as follows:

$$ET_0 = (0.288 + 0.0019 \times JD)Go \times \tau \tag{2}$$

$$ET_0 = (1.339 - 0.00288 \times JD)\ Go \times \tau \tag{3}$$

Expression 2 governs Julian days (JD)≤220 and expression 3 governs Julian days (JD)>220. ET_0 is the transpiration of a reference crop defined as an extensive surface of green well-watered grass. Transpiration of other crops is derived by multiplying reference transpiration by specific crop coefficients. JD is the Julian Day number, G_0 is the outside solar radiation, and t is the overall greenhouse transmissivity to solar radiation. These two expressions form a control logic in EnergyPlus Energy Management system as an internal gain dependant on solar irradiance arriving into the greenhouse to dynamically estimate cooling effect resulting from plant transpiration. In doing so the calibrated model is used to represent total heating and cooling requirements of the ICTA building in the following two scenarios: (i) ICTA building with iRTG incorporated; (b) ICTA building without iRTG and with the roof structure designed to conform to the statutory thermal resistance value of 0.41 W/m^{2}K.

The probable difference between the two aforementioned scenarios is the overall benefit derived from iRTG to ICTA building.

Results and discussion

Calibration results

As noted earlier, a high-fidelity calibrated model is defined to have the ability to reproduce reliable environmental and energy predictions which demonstrate the model capturing sufficient thermo-physical and operational details. Extensive building design information and as-built floor plans was used to create the building geometry in DesignBuilder Software Ltd (version 6.0.1). Using a version control method, 23 successive model versions were progressively refined to achieve simulation results in line with ASHRAE Guide 14 limits. While HVAC operational schedules, fabric thermophysical properties and site-specific weather data were kept consistent throughout, primary plant efficiencies and internal gains were updated (using EnergyPlus version 8.9) to produce energy and environmental values within acceptable error margins of monitored data. Figure 3 shows the magnitude of iRTG hourly simulation errors (simulation subtracted from error) as recommended in Royapoor (2015) for two weeks (in 2015) that are representative of winter and summer operational characteristics (i.e., average season temperatures without rain episodes or other external influences that can altered building operation system). The MBE and CV (RMSE) values for the space temperature prediction accuracies are 2.6% and 11.5% respectively.

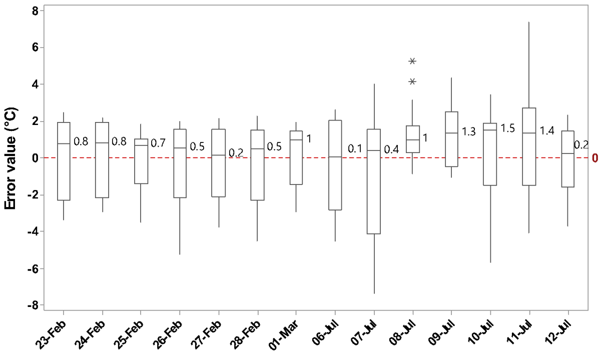


Figure 3: Hourly temperature boxplot of simulation errors across 2 weeks (winter and summer)

Quite clearly despite falling within ASHRAE acceptance criteria, there are large under and over-predictions values of 7.3°C and -7.4°C (both occurring in summer months) that demonstrate the difficulty of reproducing stochastic behaviours (i.e. window opening operations enacted by iRTG researchers) in a deterministic model. Note that the largest errors occur in summertime when stochastic window opening occurs with greater frequency.

Similarly, Figure 4 represent 2015 measured and simulated electricity values at monthly intervals that produce MBE and CV(RMSE) values of 2% and 10% respectively. While achieving ASHRAE monthly acceptance criteria of ±5% and <15% for MBE and CV(RMSE) indices, a progression of this work would be to attempt and produce acceptance criteria at hourly intervals that requires capturing the operational characteristics of the building in a more focused manner. No particular trend exists in the seasonally related magnitude of errors, with the maximum under and over-predictions of 1.8% (Dec) and -1.2% (May) which in summation produces an overall model annual over-prediction of 2% (15MWh).

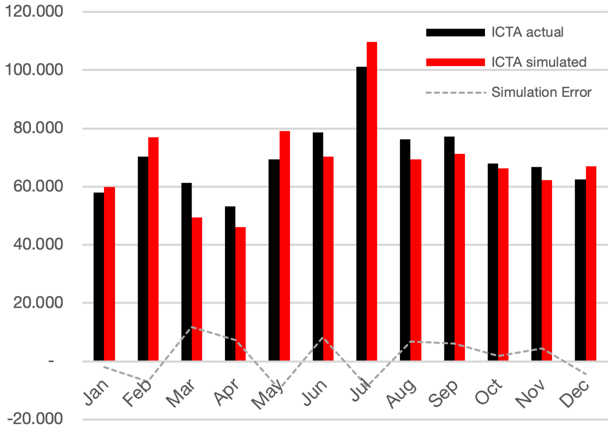


Figure 4: Measured and simulated monthly HVAC consumption and simulation error

Unidirectional and bidirectional thermal performance

Buildings and greenhouses have different thermal and operational requirements according to their purpose. Different flows will be able to be identified by examining these requirements and its performance: (i) Laboratories and offices were kept at an average temperature of 22.14ºC and 23.71ºC, respectively, during 2016. Both also need specific air renovations (greater for labs, to maintain a +10Pa air pressure) and are naturally ventilated according to the operation system of the building, which means, energy flows enriched with CO$_2$ that are spread to the environment; (ii) Greenhouse climate conditions varies with crop necessities and according to plant growth metabolism; 13º - 18ºC should be achieved during night and 21º - 26ºC during day. The translucent nature of the rooftop facilitates to achieve target day temperatures, enhancing the greenhouse effect. Automatic window-opening controls cool down the greenhouse with natural ventilation when the greenhouse is overheated (>26ºC). Higher CO$_2$ concentrations also benefits rapid plant growth.

The physical connectivity of these systems allows recycling their output flows among the iRTG-ICTA system (see Figures 5 and 6). In this section, thermal performance of heat flows is reported from real data collected during 2016.

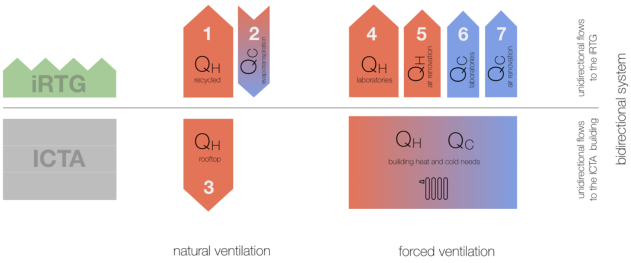


Figure 5: Bidirectional heat and cooling flows and their associated origin within the ICTA – iRTG system. Qh indicates heat flows and Qc cold flows.

Following, the natural heat and cooling flows from ICTA building to iRTG are described:

1. Flows recycled from natural ventilation of ICTA building (see Figures 5 and 6); mainly via 4 atriums (flow titled '1C', which across the annual cycle is on average +1.06ºC warmer than the iRTG air temperature) and the double skin façade (flow 1B, on average +0.43ºC warmer than iRTG air temperature), as well as the thermal inertia of the iRTG floor (flow 1A, where slab temperature is +1.07ºC warmer on average and up to +2.80ºC warmer than the iRTG air temperature in colder seasons).

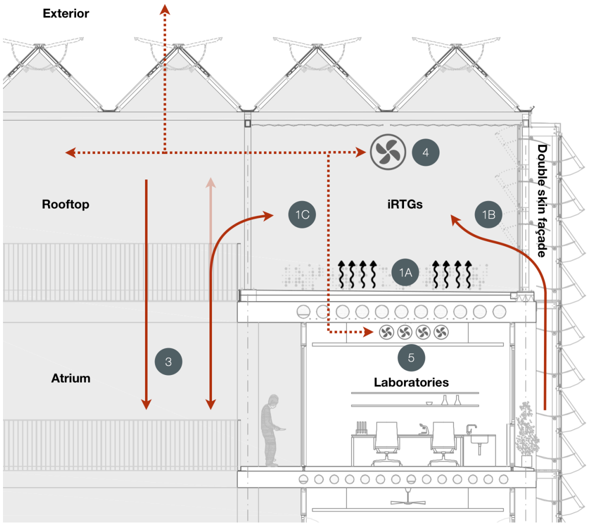


Figure 6: Main thermal flow paths

Regarding these flows, it is important to remark that the architectural connection between the iRTG and the atriums and the double skin façade can be modified with a thermal and shading mobile screen that can help isolate the greenhouse when needed to avoid thermal loss in winter or overheating in summer.

2. Evapotranspiration of plants and their capabilities to cool down the environment with the absorbed solar radiance as noted earlier and expressed in formulae 2 and 3.

The natural heat flows from iRTG to ICTA building are as follows:

3. Corresponding to the insulation effect of iRTG and ICTA building rooftop as a layer of thermal-energy recovering system due to the greenhouse effect. During 2016, the rooftop mean temperatures (5th level) were +1.76ºC compared with the 3rd level, +3.03ºC respect to the ground level and +6.48ºC respect to the exterior (see Figures 5, 6 and 7).

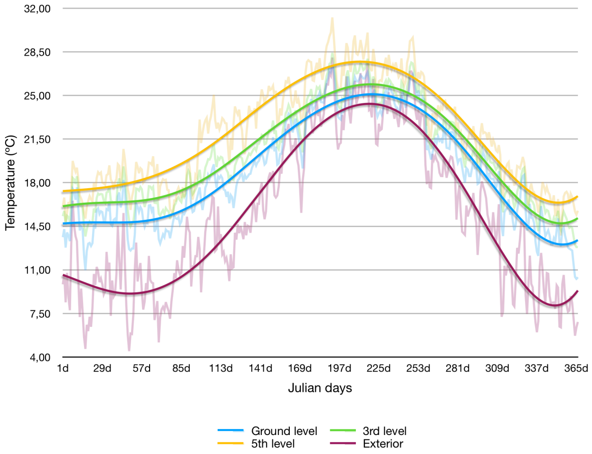


Figure 7: Annual exterior and interior ICTA building temperatures (2016)

The following points describe the forced heat and cooling flows via air handling units (AHUs) from ICTA building to the iRTG:

4. Exhaust air from laboratories to heat the iRTG when needed. During 2016, in colder periods and outside daylight times (18h to 8h), the annual average temperature in the labs was +4.58ºC compared with the iRTG temperature (see Figures 5 and 6). Considering that 10% of nominal flow extraction of 11,000 m^3/h from the AHUs of the South-East façade can be delivered to the SE-iRTG, 7MWh or 55 kWh/m^2 of annual heat flows are obtained. In 2015, 2.2 MWh or 17 kWh/m^2 of annual heat flows were obtained from June to December. No building temperature registers were stored before.
5. Air renovation from offices, potentially used to heat the iRTG when needed. Comparing again the mean temperature of 2016 from 18h to 8h, offices are +6.00ºC hotter and thus, have the potential to heat the iRTG (see Figures 5, 6 and 8).

6, 7. Air renovation from labs and offices, potentially used to cool down the iRTG when needed. Cooler iRTG temperatures compared with the exterior have been obtained during its operation in intermediate seasons (March – June). This will be deeply investigated in further research.

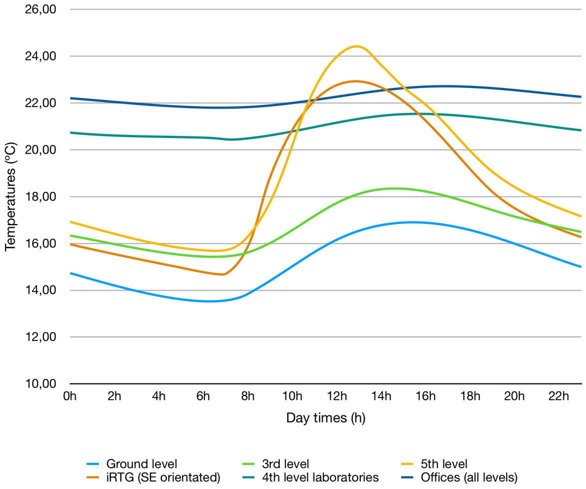


Figure 8: Daily average interior temperatures in the ICTA building (2016)

Simulation results

This section reports the simulation results of the energy simulation of the calibrated ICTA-iRTG model in order to quantify the energy benefits of the bidirectional connection of the greenhouse with the building:

1. *From the building to the greenhouse:*

For this situation, a simulation analysis was done for the same iRTG placed on the ground instead of being in the ICTA building. By heating this freestanding greenhouse to maintain the same temperature obtained in the integrated ICTA's iRTG, 341.93 kWh/m^2 where needed on average for 2015 year simulation (Nadal et al. 2017). Thus, this can be understood as recovered energy flows from the building which would be lost without the iRTG insulation effect (see Figure 9), so extra 43.78 MWh could be needed annually.

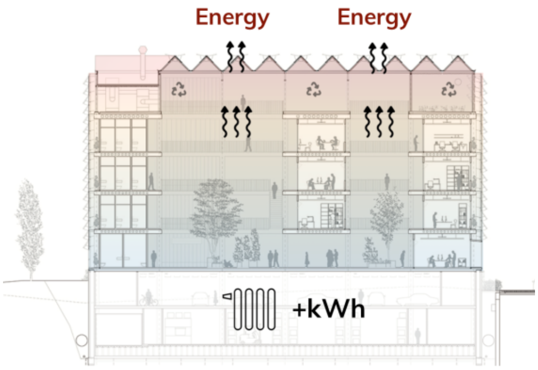
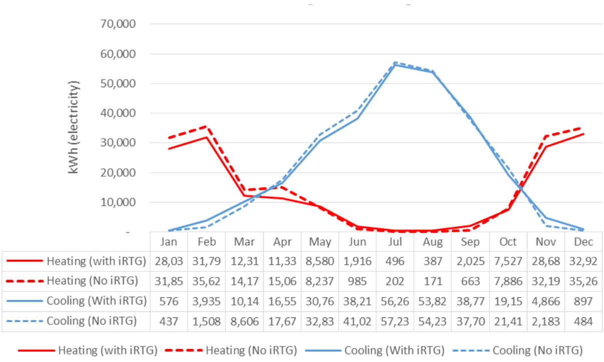


Figure 9: Scheme of the heat recovered from the building to the iRTG.

2. *From the greenhouse to the building:*

Figure 10 demonstrates calibrated model simulation results for ICTA building with and without an iRTG (using 2015 site-specific weather files). Note that both heating and cooling demands are administered across the year as has been the case in the real building in order to avoid excessive temperature swings due to the critical nature of lab and iRTG operations. Simulation results principally point to a larger heating-related saving with an annual total of 16.3 MWh$_e$ (corresponding to 31.9 kWh$_e$/m^2/yr) of reduced annual heating-related GSHP electrical duty resulting from the additional thermal buffeting effect of the iRTG. While simulated cooling benefit of the iRTG remains much smaller (1381 kWh$_e$ annually corresponding to 2.7 kWh$_e$/m^2/yr of reduced cooling duty). The simulation results indicate a consistently beneficial heating related impact of iRTG, yet the cooling-driven benefits of iRTG are reflected in spring and summer months only, with a reversed impact in winter months (Nov-Mar).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating (with iRTG)	28,03	31,79	12,31	11,33	8,580	1,916	496	387	2,025	7,527	28,68	32,92
Heating (No iRTG)	31,85	35,62	14,17	15,06	8,237	985	202	171	663	7,886	32,19	35,26
Cooling (With iRTG)	576	3,935	10,14	16,55	30,76	38,21	56,26	53,82	38,77	19,15	4,866	897
Cooling (No iRTG)	437	1,508	8,606	17,67	32,83	41,02	57,23	54,23	37,70	21,41	2,183	484

Figure 10: Heating and cooling simulated loads for the ICTA and the ICTA-iRTG systems

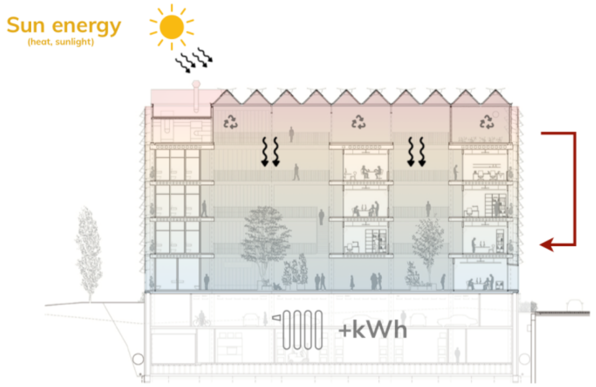


Figure 11: Scheme of the heat recovered from the iRTG to the building

Given that the calibrated model was set up to execute the cooling effect of solar-radiance driven plant transpiration (via EnergyPlus EMS control logic), this cooling effect supersedes the 'green-house' effect of iRTG at months with higher availability of solar irradiance. It is therefore critical to examine more closely the underlying principles of cooling due to plant transpiration. The simulated results suggest that an optimum point exists at which an iRTG can create an additional cooling duty. At that stage the greenhouse effect of an iRTG can exceed plant-induced cooling effect. Generating simulation results at hourly time steps with segregated heat gains, plant cooling effects and building cooling load can enable a closer examination of the cooling dynamics of an iRTG.

Future work

The EnergyPlus model fidelity will be further studied by (i) examining the temperature prediction accuracy of the model in a number of nominated spaces within the building and (ii) using hourly energy consumption data to calibrate the model. The dynamics of plant transpiration and the magnitude of its resultant cooling will be examined separately across the annual cycle and at hourly intervals to more adequately capture its time and irradiance dependencies.

Conclusion

Reducing energy needs in buildings are a key driver to decarbonise cities and the wider economy and a main component in trying to achieve the upcoming sustainability challenges. This work attempted to illustrate the possibilities of integrating urban agriculture into the building form using ICTA building as a real-world demonstrator. Actual 2016 data illustrated an injection of 55 kWh/m^2/yr of forced-ventilation heat into the building's integrated rooftop greenhouse (iRTG). A calibrated model capable of reproducing hourly temperature and monthly energy consumption data to ASHRAE acceptance criteria was used to quantify the bi-directional energy symbiosis between ICTA building and iRTG. Using 2015 weather data, the simulation results indicate iRTG has recovered an equivalent of 341.93kWh/m^2/year of thermal energy from the ICTA building, while the additional insulating impact of the iRTG has been equal to 31.9 kWh/m^2/year of thermal energy. However, the potential cooling impact of iRTG via plant transpiration requires more in-depth investigation of the dynamic causes involved in order to fully quantify both heating and cooling benefits of iRTG.

It has also to be pointed out that the case study presented here is an approach to improve building's envelope characteristics for both new and existing building stock by gaining thermal insulation and passive solar energy. Moreover, the results presented are in basis of Mediterranean weather climate and thus, the iRTG concept can be also replicable in other regions of the world: USA west coast, South of Chile or some African or Australian regions. Real world demonstrators are needed in the future to further investigate, quantify and proof the multiple benefits of iRTGs and their role to create low-carbon, resilient and sustainable buildings.

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