

1 **Building-Integrated Rooftop Greenhouses: An Energy and Environmental Assessment in the**  
2 **Mediterranean Context**

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25 **Abstract**

26 A sustainable and secure food supply within a low-carbon and resilient infrastructure is encapsulated in  
27 several of The United Nations' 17 sustainable development goals. The integration of urban agriculture in  
28 buildings can offer improved efficiencies; in recognition of this, the first south European example of a fully  
29 integrated rooftop greenhouse (iRTG) was designed and incorporated into the ICTA-ICP building by the  
30 Autonomous University of Barcelona. This design seeks to interchange heat, CO<sub>2</sub> and rainwater between  
31 the building and its rooftop greenhouse. Average air temperatures for 2015 in the iRTG were 16.5°C  
32 (winter) and 25.79°C (summer), making the iRTG an ideal growing environment. Using detailed  
33 thermophysical fabric properties, 2015 site-specific weather data, exact control strategies and dynamic soil  
34 temperatures, the iRTG was modelled in EnergyPlus to assess the performance of an equivalent  
35 'freestanding' greenhouse. The validated result shows that the thermal interchange between the iRTG and  
36 the ICTA-ICP building has considerable moderating effects on the iRTG's indoor climate; since average  
37 hourly temperatures in an equivalent freestanding greenhouse would have been 4.1°C colder in winter and  
38 4.4°C warmer in summer under the 2015 climatic conditions. The simulation results demonstrate that the  
39 iRTG case study recycled 43.78 MWh of thermal energy (or 341.93 kWh/m<sup>2</sup>/yr) from the main building in  
40 2015. Assuming 100% energy conversion efficiency, compared to freestanding greenhouses heated with  
41 oil, gas or biomass systems, the iRTG delivered an equivalent carbon savings of 113.8, 82.4 or 5.5  
42 kg.CO<sub>2</sub>(eq)/m<sup>2</sup>/yr, respectively, and economic savings of 19.63, 15.88 or 17.33 €/m<sup>2</sup>/yr, respectively. Under

43 similar climatic conditions, this symbiosis between buildings and urban agriculture makes an iRTG an  
44 efficient resource-management model and supports the promotion of a new typology or concept of buildings  
45 with a nexus or symbiosis between energy efficiency and food production.

46

47 **Keywords**

48 Rooftop greenhouse, Building performance simulation, Measured energy data, Energy Plus, Energy-food  
49 nexus, Building-rooftop greenhouse symbiosis.

50 **Abbreviations:**

51 ICTA-ICP, Institute of Environmental Science and Technology (ICTA) and Catalan Institute of  
52 Paleontology (ICP).

53 iRTG, Integrated rooftop greenhouse

54 RTG, Rooftop greenhouse

55 UA, Urban agriculture

56

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58           **1       Introduction**  
59

60   Buildings account for approximately half of the world's primary energy consumption [1–3], and agriculture  
61   and food production are reported to consume between 13–15% of total energy in developed countries [4–  
62   6]. Greenhouses are one of the most energy-demanding components of the agricultural industry [7–9]  
63   because ideal climatic conditions are created by closely controlling internal temperature and humidity levels  
64   for satisfactory plant growth in central and northern Europe.

65   While the decarbonisations of these two sectors require different solutions, an interesting possibility exists  
66   with an urban agriculture concept in which additional efficiencies can be derived from the integration of  
67   buildings and food production. A rooftop greenhouse (RTG), whereby soil-free farming methods such as  
68   hydroponics or aeroponics [10–12] may be integrated into a building, is an example. Although considerable  
69   amounts of non-renewable energy are conventionally used to operate greenhouses in central Europe, an  
70   integrated method could help decarbonise greenhouse-based food production and promote more efficient  
71   and sustainable greenhouse heating [13,14]. Empirical data are missing in this area, and this has formed the  
72   foundation of this work: full annual results are presented for the operational characteristics of the world's  
73   first case of a fully-integrated rooftop greenhouse for scientific research. Within this article, ICTA-ICP  
74   refers to the entire building under study; the integrated rooftop greenhouse (iRTG) is used to refer to the  
75   rooftop greenhouse.

76   The objective of this paper is, therefore, (a) to report the measured annual data that outlines the symbiosis  
77   between the iRTG and the building in energy terms and (b) using computer simulation, to quantify the  
78   heating energy that iRTG has passively and actively recycled from the ICTA-ICP. The reduced  
79   environmental impact resulting from this integration is then calculated using  $\text{kg.CO}_2(\text{eq})/\text{m}^2/\text{yr}$  as the index.  
80   In doing so, the advantages offered by the iRTG concept relative to a conventional freestanding greenhouse  
81   are highlighted. While reporting the first scientific case for support on the application and feasibility of an  
82   iRTG; the findings also redefine a unique typology or concept of building design that can have a nexus or  
83   symbiosis between energy efficiency and food production worldwide as a strategy in support of food  
84   security and green urbanism. While seeking to offer an original perspective on the theme of integration of  
85   greenhouses in buildings and demonstrating the viability of this concept, this work also highlights the need  
86   for further research in the adaptation of iRTG concept under various urban energy and operational systems  
87   and climatic conditions around the world.

88     **1.1     Global urbanisation and the food challenge**

89     The United Nations, in its 2010 perspective, noted that more people live in urban settings than in rural  
90     areas. The projection of this trend is that world urbanisation will increase from 50% in 2009 to 69% in 2050  
91     [15]. A total of 75% of the EU population currently lives in cities, a percentage that is expected to rise to  
92     80% by 2020 [16]. This high concentration of people in cities has major socio-economic ramifications, and  
93     food production and its supply and security requires closer examination [17].

94     According to figures provided by the Food and Agriculture Organization of the United Nations (FAO),  
95     almost a billion people suffer from malnutrition, and four hundred million are chronically undernourished  
96     [18]. Conversely, urbanisation has generated a two-pronged nutritional burden: nutritional deficiencies and  
97     the emergence of over-nutrition among vulnerable groups in urban areas [19]. In recognition of this, the  
98     concept of urban agriculture (UA) seeks to offer innovative solutions to ensure the environmental and  
99     economic sustainability of food supplies within urban contexts and also to promote food of high nutritional  
100    quality.

101    Urban agriculture ranges from entirely commercialised agricultural facilities to production at the household  
102    level [20] and usually complements rural agriculture [21]. Urban agriculture is a historical reality in  
103    developing countries [22,23], where even today 800 million people are engaged in urban agriculture,  
104    producing 15 to 20% of the world's food [24]. It is believed that 10-20% of the nutritional needs of families  
105    living in urban areas in developing countries are met by the consumption of fruits and vegetables from  
106    urban agriculture [21].

107    Because of its adaptability to any built environment and typology, urban agriculture's benefits encompass  
108    economic, social and environmental elements [25]. In urban areas of relatively high residential density with  
109    mixed land use and limited access to green spaces for food production, rooftop greenhouses (RTGs) can  
110    provide the opportunity for cities to produce high-nutrient food with maximum efficiency, minimising  
111    production and transport costs and optimising space use in a built environment where buildings can foster  
112    food production.

113     **1.2. Conventional greenhouses**

114    Greenhouses, regardless of their degrees of complexity, attempt to provide ideal conditions for adequate  
115    plant growth throughout the year [26,27]. The principal regulated parameters are light, temperature,  
116    humidity and air quality [28–30]. The origin of the greenhouse goes back to ancient times. They were

117 popular during 15th to 18th centuries in France, England and the Netherlands, but their use for commercial  
118 production began only in the mid-19th century, increasing after 1945 [26] and culminating in today's  
119 widespread deployment in Europe. More specifically, the estimate for the European Mediterranean region  
120 is more than 200,000 ha of in-use greenhouses in 2006 and 1,950,000 ha by 2010. Spain had 53,842 ha  
121 during 2005, and in 2009, Almería possessed a total of 27,000 ha [31].

122 Specifically, the Mediterranean area ecosystems have the characteristics of several regions in the world,  
123 such as southern Chile, California, the European Mediterranean basin, Cape Province in South Africa, and  
124 southwest Australia [32,33]. In the European Mediterranean basin, the development of Mediterranean  
125 horticulture was reshaped by the energy crisis in the 1970s, when low-cost plastics and local materials were  
126 used to build the first generation of widely deployed greenhouses. A basic Mediterranean greenhouse is  
127 characterised by large inner volumes within a low-cost structure (i.e., low-cost polyethylene roof and walls),  
128 total transparency, natural ventilation, no heating, limited use of climate control systems, and stability with  
129 respect to wind and thermal screens [34,35]. The seasonal operational regime of Mediterranean greenhouses  
130 seeks the maximisation of solar irradiation and the minimisation of thermal energy loss (autumn and  
131 winter), as well as the reduction of excess temperatures in spring and summer [36–38]. High temperatures  
132 and high solar radiation can affect the development of crops, especially tomatoes [39,40], so the use of  
133 shading and efficient ventilation systems is required. Natural ventilation is the most economical method to  
134 reduce excess heat build-up in greenhouses, but as it is totally dependent on external conditions, it may be  
135 insufficient [41]. The most efficient systems use electrically powered forced ventilation, which  
136 understandably require electricity estimated at 100,000 kWh annually per greenhouse hectare, under high  
137 outside temperatures and intense solar radiation (common summer conditions in Mediterranean countries);  
138 such systems use a static ventilation fan pressure of approximately 30 Pa on the leeside or the lee end of  
139 the greenhouse with two fans placed 8–10 m apart and an inlet opening on the opposite side of least 1.25  
140 times the fan area and an air speed of 0.5 m/s [37].

141 Generally, some energy use is unavoidable and results in energy accounting for 10–30 percent of total  
142 production costs (depending on the region). In Mediterranean areas, the annual energy consumption for  
143 space conditioning is 139–444 kWh/m<sup>2</sup>, which arises from winter night heating requirements (and is  
144 increasingly being adopted [37]), although the majority of Mediterranean greenhouses remain unheated.

145 The high cost of energy, climate concerns and new environmental policies have brought about the challenge  
146 of reducing the energy input into the greenhouse system while maintaining or increasing production per  
147 unit of energy [37,42].

148 **1.3 Energy and food production in buildings**

149 Modern cities are unfortunately dependent for the most part on a consistent supply of fossil fuels, and the  
150 urban lifestyle is becoming more energy-intensive worldwide [43]. Global demand for fossil fuels has risen  
151 more rapidly than production; in the build-up to 2014, energy use worldwide grew by one-third, driven  
152 primarily by developing areas such as India, China, Africa, the Middle East and Southeast Asia [44].

153 The energy used by the building sector continues to increase; worldwide, 30-40% of all primary energy is  
154 used in buildings [45]. One third of energy-related CO<sub>2</sub> emissions and two thirds of halocarbon emissions  
155 worldwide are attributed to buildings [46]. Electricity consumption in the commercial building sector  
156 doubled between 1980 and 2000 and is expected to increase by another 50% by 2025 [47]. Nonetheless,  
157 the Intergovernmental Panel on Climate Change indicates that buildings provide the most economic  
158 mitigation potential for reducing CO<sub>2</sub> emissions, with a global potential of cost-effectively reducing  
159 approximately 29% of the projected baseline emissions by 2020 in the residential and commercial sectors  
160 [48].

161 On the other hand, food supply to urban areas is a complex issue and a major energy consumer. The flow  
162 of food to cities follows a complex and linear model [10] defined by importing resources and exporting  
163 emissions, leading to high lifecycle utilisation per kg food unit of energy resources, waste and CO<sub>2</sub>  
164 emissions [49]. Where the concept of food production and building energy use has been united is in the use  
165 of the rooftop greenhouse (RTG) in Mediterranean cities; these have reduced building cooling and heating  
166 loads due to improved roof insulation, with reductions of up to 40 percent being reported for specific case  
167 studies [50].

168 The RTG concept has also been adapted in urban areas of Canada and the US, with examples including  
169 Lufa Farms (31,000 m<sup>2</sup> RTG in Montreal), The Vinegar Factory (830 m<sup>2</sup> RTG in Manhattan, NYC),  
170 Gotham Greens (15,000 m<sup>2</sup> RTG in New York) [51,52], and Sky vegetables (743 m<sup>2</sup>) [53] and The  
171 Greenhouse (130 m<sup>2</sup>) on the roof of Public School 333 [54], both in NYC. Also in NYC, the Arbor House  
172 with a 1000 m<sup>2</sup> greenhouse, using waste heat from below to heat a greenhouse building [55], captures 225  
173 MWh / year of waste heat (26 kW avg). Research or social benefits have remained the driving forces for

RTG adaption in other countries; for example, Japan, specifically Tokyo, has developed Pasona HQ Tokyo Urban Farm (4,000 m<sup>2</sup> RTG) [56]. In Europe, Germany has some examples of implementation (In Farming of Fraunhofer, UMSICHT) [57]; the United Kingdom is currently constructing the new Urban Science Building at Newcastle University with a rooftop greenhouse planned [58], and Urban farmers in Switzerland (250 m<sup>2</sup>) and the opening in 2016 in The Hague of the UF002 De Schilde (1900 m<sup>2</sup>) [59] are also examples. Spain has the first building designed principally from the start to have an integrated building RTG (i-RTG), the ICTA-iRTG at the Autonomous University of Barcelona (UAB) [60]. The driving design principles were the creation of a building that enabled a synergetic relationship between food production and building management by recycling and integration of energy, CO<sub>2</sub> and water. Such a symbiosis is hoped to reduce the environmental impacts of buildings and ultimately cities. Inaugurated in 2014, this integrated greenhouse is producing four crops per year: two crops of tomatoes “*cor de bou*” (ox heart at a productivity rate of 16.2 kg per m<sup>2</sup>) and two intermediate crops of lettuce. This innovative agricultural production system showcases how the building integration of a rooftop greenhouse (i-RTG) improves a building ‘metabolism’ by the direct flow exchange of energy, water and CO<sub>2</sub> [60].

#### 1.4 The iRTG concept

The *Integrated Rooftop Greenhouse* (iRTG) is presented from an industrial ecology perspective as a system that incorporates urban agriculture into new or existing building rooftops in the city and consists of a greenhouse interconnected with its host building in terms of energy, water and CO<sub>2</sub> flows. As a new approach to sustainable urban food production, iRTG is based on four main pillars: (1) the incorporation of the concept of symbiosis between a rooftop greenhouse and the building by means of reusing residual resource flows (energy, water and CO<sub>2</sub>), (2) the inter-connectivity of resource flows between iRTG and the building, in that the greenhouse is not an isolated element outside the main building envelope, but an integral part that requires consideration at the concept stage of building design, (3) environmental impact reduction and high energy efficiency as a critical concept, (4) facilitation of the production of quality food using building rooftops and generation of food production self- sufficiency in the urban context. Given the global need for responsible energy consumption in buildings and the urgency to secure food supplies, the contribution of this project is principally a design concept that creates a nexus or symbiosis between building energy flow and food production. Thus, the expansions of cities can be seen as an opportunity and not as an obstacle to maintain a secure food supply and energy efficiency.

203 The iRTG concept seeks to generate changes in the current conception of buildings as unproductive  
204 elements. Through iRTG, a building can be viewed as an element that, in addition to meeting the need for  
205 cover and protection, has the ability to support food production - regardless of its location around the world.  
206 Megacities (Shanghai, Mexico City, Osaka, Beijing, NYC and others) and developing cities have  
207 considerable artificialised areas and huge populations; the development of iRTG's affords the opportunity  
208 to produce and consume zero km vegetables with no increases in the energy consumptions of the buildings.  
209 That is, the concept of iRTG seeks to change the heterotrophic ecosystem of cities to an autotrophic urban  
210 ecosystem that does not require food imports from rural areas.

211 Despite the various benefits that can derive from the iRTG, there are only a limited number of studies  
212 around the world that address the issue, and these are from a mostly theoretical point of view. In Singapore,  
213 Astee (2010)[61] explored the feasibility of the implementation of an iRTG for growing vegetables in  
214 blocks of public housing in the city of Tampines; in New York, the architectural firm Kiss + Cathcart  
215 Architects provides the services of integrating food production into the building through hydroponics  
216 farming systems, though there is no information on actual cases [62]. In Brussels, the architectural firm  
217 Lateral Thinking Factory has proposed the theoretical design of an Integrated Building Greenhouse in the  
218 city of Louvain la Neuve, but the information is limited [63]. In Berlin, the Watergy Prototype 2 is being  
219 built, in which the greenhouse provides fruit by utilising the residual air of the building [64]. To date  
220 however, the only case designed and built for scientific research in urban agriculture is the ICTA-iRTG.  
221 Part of the importance of this case study lies in it being the only scientifically documented case that provides  
222 current data for comparison with other urban agriculture projects.

223           **2       The case-study building**  
224

225           **2.1     Overview**

226 Located at the Autonomous University of Barcelona (UAB) campus (Bellaterra, Barcelona), the ICTA-ICP  
227 building (see Fig. 1) houses the headquarters of the Institute of Environmental Science and Technology  
228 (ICTA) and the Catalan Institute of Paleontology (ICP). The building was awarded LEED-Gold®  
229 certification (Leadership in Energy & Environmental Design) by the U.S. Green Building Council for its  
230 building-integrated agriculture philosophy, multifunctionality and passive systems that promote energy  
231 efficiency.

232 The building has a surface area of 7,200 m<sup>2</sup> distributed over 7 floors (5 levels above ground and 2 below).  
233 The two sub-ground levels are used for car parking and storage, while the first four levels above ground are  
234 equipped with offices, laboratories and common areas; and the fifth level houses four greenhouses for food  
235 production (measuring 128 m<sup>2</sup> each). Currently, only two of the four greenhouses are functional; this work  
236 reports data from one of these (referred to as the iRTG). The main structure and floors of the ICTA-ICP  
237 building are of reinforced concrete; the internal walls are recycled wood, and the roof and outer skins are  
238 made of polycarbonate, which facilitates an ideal environment for crop growth and daylighting the interior  
239 spaces.

240 The translucent nature of the building fabric facilitates passive heating in winter and aids displacement  
241 ventilation during summer (via 4 internal atriums and a double-skin facade). Displacement natural  
242 ventilation is facilitated through the opening of windows and skylights in the building outer skin. The  
243 ventilation simply renews the air as outer skin inlets allow fresh intake to travel horizontally into offices  
244 (via internal windows) and rise vertically via four internal atria before exhausting through the skylights  
245 (zenith ventilation). A concrete structure with high thermal inertia, coupled with building passive comfort  
246 systems, maintains a thermal anchor to minimise the active heating and cooling input of a ground-source  
247 heat pump (only to the internal workspaces and the laboratories). The iRTG does not have designated  
248 mechanical heating but, as outlined in the next section, benefits from the building's thermal stability. Its  
249 integration with the building is unidirectional (from building to greenhouse only). In this sense, the iRTG  
250 utilises exhaust air from the building for heating; the higher CO<sub>2</sub> concentration and humidity of this residual  
251 air also act as natural fertilisers to increase crop yields. The integration is direct if the residual air comes  
252 from laboratories (discharged directly into the iRTG via service ducts) or indirect if it comes from the  
253 common areas of the building (arriving into the iRTG via four atria).



254

255 Fig. 1. The ICTA-ICP building and the iRTG.

256 The iRTG greenhouse has modifications in form and building materials compared to the standard typology  
 257 of traditional Mediterranean greenhouses to reflect its building-integrated nature. To comply with the  
 258 Spanish Technical Edification Code (CTE) (RD 314/2006 (BOE 2006)) and fire safety laws (RD 2267/2004  
 259 (BOE 2004), Law 3/2010 (BOE 2010), the greenhouse galvanised steel structure was reinforced to  
 260 withstand horizontal wind loads. Polycarbonate sheeting was used for the roof and walls because of its high  
 261 solar transmittance.

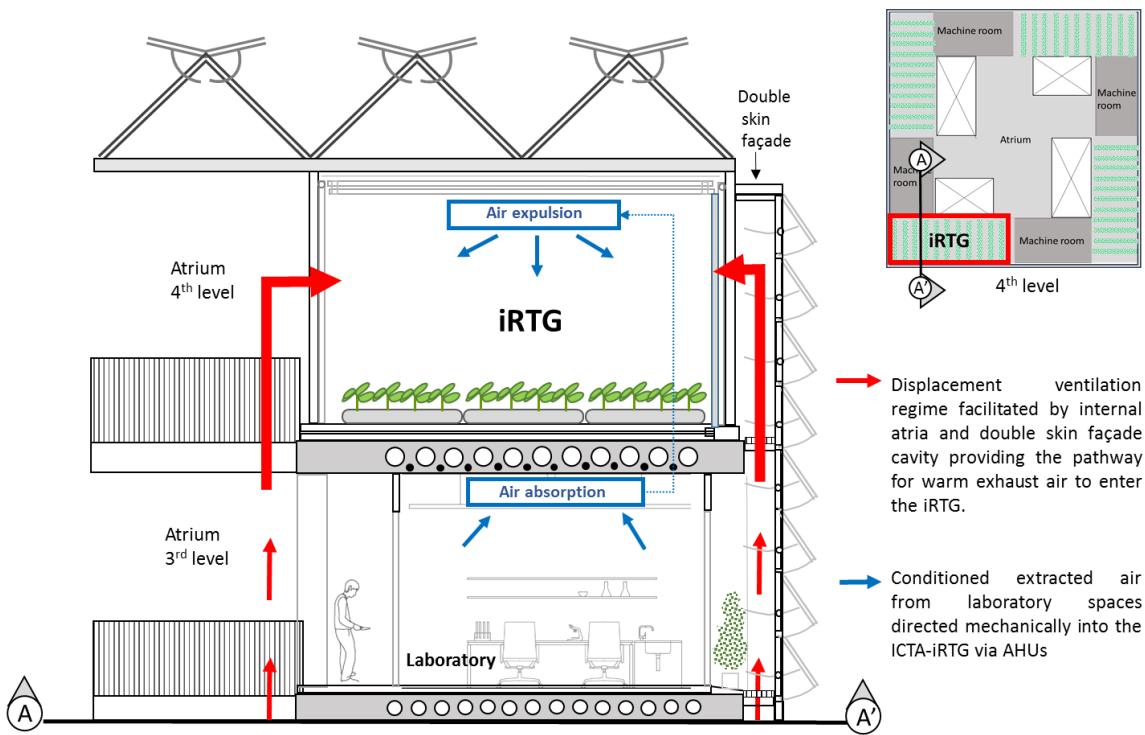
262 The iRTG reported in this work has an area of 128 m<sup>2</sup> (6.55 m wide × 19.55 m long) with a two-span gable  
 263 roof with 45° roof slopes (4.20 m high at the gutter and 5.80 m at the ridge). Awning windows mounted on  
 264 sidewalls with a maximum opening angle of 45 degrees provide ventilation. The crop area is 84.34 m<sup>2</sup> and  
 265 achieved a total production of 989 kg of tomatoes during the spring-summer period, 85% of which met  
 266 commercial product requirements (with the remainder edible but not marketable). The greenhouse uses a  
 267 thermal screen and low-density polyethylene (LDPE) curtains to both improve internal heat conditions and  
 268 insulate the space from the rest the building and excessive influence of the outer skin. The thermal screen  
 269 is similar to those deployed across the Mediterranean region to reduce incident solar radiation. Both the  
 270 curtains and the thermal screen are operated automatically as a function of the temperature inside the  
 271 greenhouse.

272

273 **2.2 Thermal exchanges and controls**

274 There are two thermal interaction paths between the iRTG and the building: the ventilation air from  
 275 occupied spaces delivered to iRTG via air handling units (AHUs) and the displacement ventilation and air  
 276 heated by solar radiation rising through the double skin cavity (that terminates at the iRTG - see Fig. 2).

277 The objective is that the cumulative effect of these heat transfers provide the iRTG with optimal thermal  
 278 conditions (14-26°C) for Mediterranean horticultural crop production in a closed system throughout the  
 279 year [65].



| Building mode     | Season                | Date              | Heating or cooling |
|-------------------|-----------------------|-------------------|--------------------|
| 1- Winter         | Winter                | 1 Dec. - 31 Mar.  | Yes                |
| 2-Intermediate A  | Spring                | 1 Apr. - 31 May.  | No                 |
| 3-Summer          | Summer                | 1 Jun. - 30 Sept. | Yes                |
| 4 -Intermediate B | Autumn                | 1 Oct. - 30 Nov.  | No                 |
| 5- Passive mode   | Weekends and holidays | All year          | No                 |

|              |          |                               |                             |
|--------------|----------|-------------------------------|-----------------------------|
| Laboratories | All year | (Depends on ongoing research) | Depends on ongoing research |
|--------------|----------|-------------------------------|-----------------------------|

286

287 At any point in the annual calendar, the ICTA-ICP building has 5 internal climates adapted to the functions  
288 of the spaces:

289 1- Laboratories, with heating/cooling to achieve a temperature range of 21-25°C to satisfy the  
290 changing needs of lab work.

291 2- Workspaces and offices, with heating/cooling and a temperature range of 17-26°C, depending on  
292 the season and the HVAC mode of operation.

293 3- Communal spaces, unheated/uncooled; the temperature is allowed to fluctuate with the season.

294 4- iRTG, unheated/uncooled; the temperature range varies as a function of the outside conditions and  
295 thermal interactions outlined in Fig. 2.

296 5- Parking and underground cellars, in freefloat mode; their temperature ranges vary as a function of  
297 outside conditions.

298

299 **2.3 Monitoring tools**

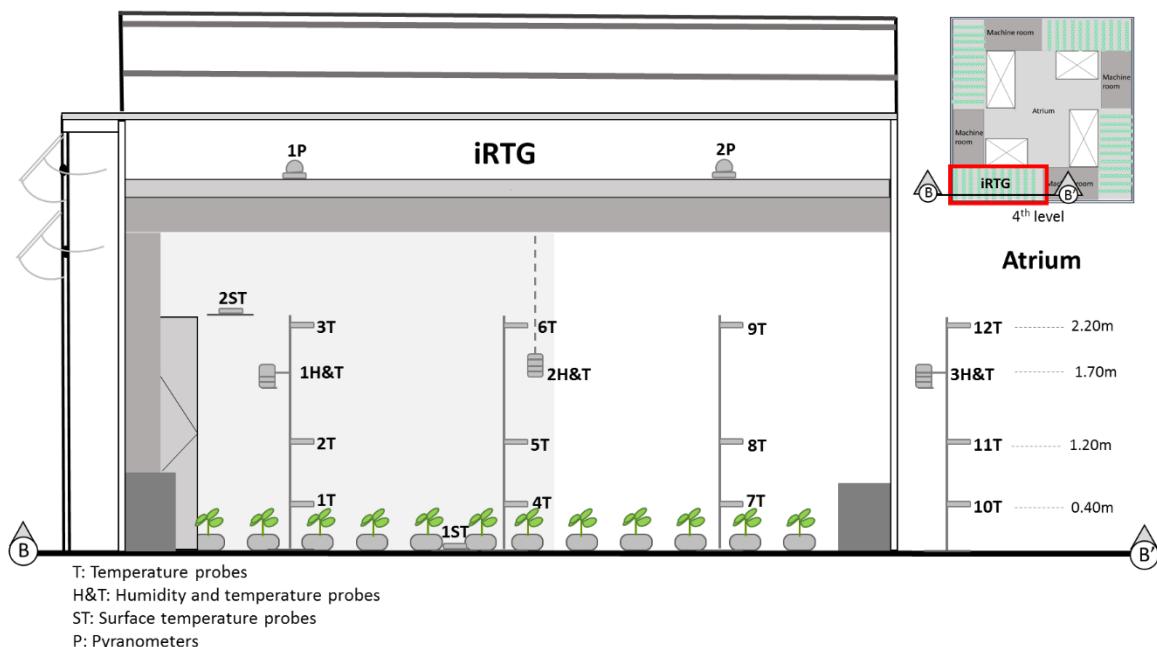
300 Two independent and complementary monitoring systems are instrumented in iRTG that were specified  
301 and programmed exclusively for this space: Siemens control software and a Campbell continuous data  
302 acquisition system. The Siemens software offers independent controls of the ICTA-ICP building and the  
303 iRTG thermal condition. Sensors and probes inside and outside the building continuously collect  
304 temperature, humidity, air quality, solar radiation and air velocity data, allowing the system to make  
305 automated decisions and interventions. The researchers are able to override automated controls and adjust  
306 the settings in response to user and crop requirements (i.e., overriding the opening of windows, temperature  
307 set points, greenhouse solar covers, etc.).

308 The Campbell data acquisition system comprises 12 temperature probes (Campbell 107 with an accuracy  
309 of  $\pm 0.18^\circ\text{C}$ ), 3 combined temperature and humidity probes (Campbell CS215 with accuracies of  $\pm 0.3^\circ\text{C}$   
310 and  $\pm 2\%$ , respectively), 2 pyranometers (Campbell LP02 with expected accuracy for daily sums of  $\pm 10\%$ )  
311 and 2 surface-temperature probes (Campbell 110PV with an accuracy of  $\pm 0.2^\circ\text{C}$ ) for energy monitoring.  
312 Additional Campbell probes also include sensors that monitor air quality, pH and conductivity of irrigation

313 water. A data logger (Campbell CR3000 with  $\pm 0.04\%$  of accuracy) takes measurements every 5 s and  
314 records the averages at 10 min intervals.

315 All sensors were pre-calibrated by Campbell. External data are obtained from the meteorological station of  
316 the building and are checked/compared with Sabadell Agricultural Park weather station (part of the  
317 Meteorological Service of Catalonia data) 5 km from iRTG. The meteorological station provides hourly  
318 averaged values.

319 All these probes are evenly distributed on four vertical supports that are erected at 0.40 m, 1.20 m, 1.70 m  
320 and 2.20 m above the iRTG floor level (see Fig. 3). Each vertical support has three temperature probes and  
321 a combined temperature and RH probe. The supports are located inside the iRTG and in the upper atrium  
322 of the ICTA-ICP building.



323  
324 Fig. 3. Probe locations within the iRTG and atrium spaces.

325 **3 Simulation Method**  
326

327 **3.1 Purpose and software description**

328 To highlight the operational energy and indoor-climate benefits derived from the integration of the iRTG  
329 greenhouse with the ICTA-ICP building, two virtual models were created; the first is a complete model of  
330 ICTA-ICP building to validate building and model fidelity, and the second is a 'freestanding' virtual model  
331 of the iRTG to quantify the heating loads of an equivalent but freestanding greenhouse (see Fig. 4). Detailed  
332 iRTG fabric thermo-physical properties and exact operational regimes provided parameter input into

333 Design Builder version 4.6 (used to create the iRTG geometry). The completed Design Builder model was  
334 used to create the input data file (IDF) for EnergyPlus (E+) Version 8.4, which enabled the energy  
335 simulation. E+ was selected because of the following:

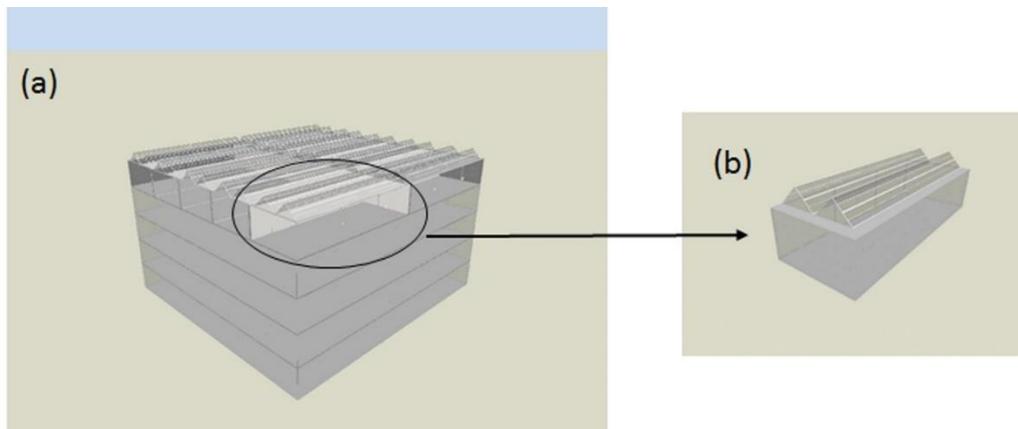
336 1- The E+ weather statistics and conversions program allow the creation of 2015 weather files using  
337 ICTA-ICP site-specific dry bulb air temperatures and relative humidity. However, solar  
338 irradiation, wind and precipitation data were compiled using the 2015 Sabadell station.

339 2- The transparent nature of the ICTA-iRTG fabric leads to substantial space-climate interactions.  
340 E+ has the ability to accept the detailed spectral optical properties of the transparent fabric and  
341 user-specified window and shading controls (see Table 2).

342 3- Schedule: the file facility in E+ can accept hourly space target temperatures, allowing the accurate  
343 replication of the iRTG internal climate and subsequent heating demand.

344 4- Zone and soil heat exchange are critical in simulating the performance of a greenhouse; KIVA  
345 software version 0.3 [66] was used to generate hourly soil temperatures and informed the  
346 freestanding iRTG model.

347 5- E+ has been demonstrated to have high accuracies for internal temperatures and load predictions  
348 [67].



349  
350 Fig. 4. (a) Design Builder model of the ICTA-ICP building to validate model prediction accuracy, (b)  
351 freestanding iRTG used to examine freestanding greenhouse conditions.

352 The manufacturer's literature and (where unavailable) the Cambridge University 2015 CES database and  
353 2013 ASHRAE Handbook (Fundamentals) were consulted to compile detailed input parameters (see  
354 Appendix Table A1). Similarly, the occupancy pattern, artificial lighting arrangement, exact operating  
355 schedules for the windows and retractable aluminised screen of the iRTG informed both the validation and  
356 freestanding modelling work.

357 Table 2. Opening regimes of the iRTG windows and retractable aluminised screen.

358

|  | Internal<br>temperature (°C) | Opening             |
|--|------------------------------|---------------------|
| Roof Windows   | 22                           | 10°                 |
|  | 23                           | 20°                 |
|  | 24                           | 30°                 |
|  | 27                           | 45° <sup>[1]</sup>  |
| Facade<br>Windows  | 22                           | 5°                  |
|  | 23                           | 10°                 |
|  | 24                           | 20°                 |
|  | 27                           | 45° <sup>[1]</sup>  |
| Reflective<br>aluminised screen <sup>[4]</sup>                                       | 31                           | 25% <sup>[2]</sup>  |
|  | 31,8                         | 50% <sup>[2]</sup>  |
|  | 32,6                         | 75% <sup>[2]</sup>  |
|  | 34                           | 100% <sup>[2]</sup> |
|  | <16                          | 100% <sup>[3]</sup> |
| [1] Maximum opening angle  |                              |                     |
| [2] Summer-only operations to prevent overheating                                    |                              |                     |
| [3] Winter-only closure to prevent thermal inversion (thermal loss)                  |                              |                     |
| [4] Reflective screen opening refers to the screen expanding to cover the iRTG below |                              |                     |

359

### 360 3.2 Optical properties of translucent material

361 Altogether, 111 data entry points were used to describe the optical properties of the translucent fabric  
362 component of the iRTG using the manufacturer's data (wavelength range: 125-15,000 nm). This proprietary  
363 corrugated polycarbonate sheet is designed for maximum light transmission in the visible spectrum. Full  
364 spectral properties were used in E+ within a bilinear interpolation using Glazing's U-Value and Solar Heat  
365 Gain Coefficient (SHGC) to calculate solar transmittance at normal incidence. Angular performance was  
366 then calculated in 10° increments and stored in E+ and interpolated for in-between values during the  
367 simulations [68].

### 368 3.3 Crop transpiration coefficient

369 Crop transpiration plays a significant role in the greenhouse climate. During the day, the crop canopy  
370 absorbs a significant amount of the solar radiation it receives and uses this energy to evaporate water  
371 through transpiration. As a result, the temperature of the greenhouse air decreases, and its humidity content  
372 increases.

373 Several formulae have been used in the literature to calculate crop transpiration. Bonachela et al. (2006)  
374 [69] provided an empirical formula for Mediterranean greenhouses as follows:

375  $ET_0 = (0.288 + 0.0019 \times JD)G_0 \times \tau$  (For Julian days (JD)  $\leq 220$ ) [1]

376  $ET_0 = (1.339 - 0.00288 \times JD) G_0 \times \tau$  (For Julian days (JD)  $> 220$ ) [2]

377 where  $ET_0$  is the transpiration of a reference crop defined as an extensive surface of green well-watered  
378 grass. Transpiration of other crops is derived by multiplying reference transpiration by specific crop  
379 coefficients. JD is the Julian Day number,  $G_0$  is the outside solar radiation, and  $\tau$  is the overall greenhouse  
380 transmissivity to solar radiation. By using the JD for every central day of each month, it was possible to  
381 calculate the percentage of outside solar radiation that the crop used for transpiration, which forms the plant  
382 cooling effect. The Energy Management System in E+ was used to create control logic that uses an  
383 independent variable (i.e., solar irradiance arriving in the greenhouse) to compute corresponding plant  
384 transpiration cooling capacity using equations 1 and 2.

385 **3.4 Surface convective coefficients**

386 Considerable uncertainties exist in convective heat transfer coefficient (CHTC) values applied in building  
387 models that are transferred into and cause large errors in the energy-prediction results [70]. Given its  
388 significance, an outline of the calculation selection is covered here. CHTC is a major energy transfer  
389 mechanism, and a multitude of different analytical and experimental methods exist that describe internal or  
390 external surface coefficients at various air velocity profiles and surface geometries. The rate by which an  
391 internal building surface loses heat is predominantly dictated by its convective coefficients, whereas  
392 external surface heat loss is dominated by air movements.

393 E+ documentation recommends the DOE-2 model to calculate CHTC values for smooth vertical surfaces  
394 with windward or leeward orientations in low-rise buildings, which closely represents the iRTG structure.  
395 DOE-2 is a hybrid full-scale CHTC model that combines the MoWiTT [71] and BLAST [19] models to  
396 dynamically calculate external CHTC using the following:

397 
$$h_{c,ext} = \sqrt{h_{c,nat}^2 + (aV_{10}^b)^2} \quad [3]$$

398 
$$h_{c,nat} = 9.482 \frac{(|T_s - T_a|)^{1/3}}{7.238 - |\cos \phi|} \quad (\text{for ascending flows (Ts>Ta)}) \quad [4]$$

399 
$$h_{c,nat} = 1.810 \frac{(|T_s - T_a|)^{1/3}}{1.382 + |\cos \phi|} \quad (\text{for descending flows (Ts<Ta)}) \quad [5]$$

400

401 where  $H_{c,ext}$  denotes external CHTC,  $h_{c,nat}$  accounts for buoyancy-driven flows (W/m<sup>2</sup>K),  $T_s$  and  $T_a$  are  
 402 surface and air temperatures (°C), and  $\phi$  is the surface plane slope angle in relation to the ground plane (°),  
 403 which makes equations 4 and 5 equal at 90° (for a vertical wall).  $a$  and  $b$  are constants outlined in Table 3,  
 404 and  $V_{10}$  represents the undisturbed wind speed measured at 10 m above ground level (m/s). E+ calculates  
 405 the roof CHTC in the same manner.

406 Interior CHTC was dynamically calculated using the TARP [72] method that computes the sum of forced  
 407 and natural convection components, with the natural component derived from expressions 4 and 5, while  
 408 the forced component is as follows:

409 
$$h_{c,for} = 2.537 W_f R_f \left( \frac{PV_f}{A} \right)^2 \quad [6]$$

410 where  $h_{c,for}$  is the forced CHTC component (W/m<sup>2</sup>K),  $W_f$  is the wind-direction modifier,  $R_f$  is the surface-  
 411 roughness multiplier, and  $P$  and  $A$  are the perimeter and area of the surface (m and m<sup>2</sup>), respectively.

412 Table 3. Constant parameters for MoWiTT model.

| Surface orientation | a                | b                 |
|---------------------|------------------|-------------------|
| Windward            | $2.38 \pm 0.036$ | $0.89 \pm 0.009$  |
| Leeward             | $2.36 \pm 0.098$ | $0.617 \pm 0.017$ |

413

414 **3.5 Model validation**

415 For model validation, site-specific direct and diffused solar irradiance, outdoor temperature and humidity  
 416 and sky conditions were used within a complete model of the ICTA-ICP building with actual indoor  
 417 temperatures and operational regimes. The complete building model enables accounting for the impact of  
 418 the main building structure and envelope on the iRTG. A succession of 17 models, each with incremental  
 419 adjustments, were used to best satisfy ASHRAE Guideline 14 (2002) on model validation using actual and  
 420 simulated hourly data [73]. This entailed determining the two dimensionless indicators of errors, mean bias  
 421 error (MBE) and cumulative variation of root-mean-square error (CV (RMSE)) using the following:

422 
$$MBE = \frac{\sum_{i=1}^{N_i} (M_i - S_i)}{\sum_{i=1}^{N_i} M_i}$$
 [7]

423 
$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i} [(M_i - S_i)^2 / N_i]}}{\frac{1}{N_i} \sum_{i=1}^{N_i} M_i}$$
 [8]

424 where  $M_i$  and  $S_i$  are the measured and simulated data, respectively, at instance i, and  $N_i$  is the count of the  
 425 number of values used in the calculation. The ASHRAE building model calibration limits on hourly data  
 426 are  $\pm 10\%$  (for MBE) and  $<30\%$  (for CV (RMSE)).

427 **4 Results and discussion**

428

429 **4.1 iRTG annual space condition**

430 The iRTG temperature data compiled by monitoring systems for the first operational year are summarised  
 431 in Table 4. This captures seasonal averages, as well as maximum and minimum temperatures, from  
 432 December 2014 to December 2015. Seasonal average temperatures range from 16.5°C in winter to 25.9°C  
 433 in summer, with a winter minimum of 6.3°C and a summer maximum of 39.7°C. Average iRTG  
 434 temperatures are, therefore, within the FAO's recommended optimum average range of 14-26°C and satisfy  
 435 the Mediterranean horticultural closed systems recommendations.

436 Table 4. Weekly iRTG and outdoor average temperatures in each season of 2015.

|                                 | Winter       |              | Spring      |             | Summer       |              | Autumn      |             |              |               |           |         |
|---------------------------------|--------------|--------------|-------------|-------------|--------------|--------------|-------------|-------------|--------------|---------------|-----------|---------|
|                                 | 21 Dec. 2014 | 19 Mar. 2015 | ICTA-iRTG   | Outdoor     | 20 Mar. 2015 | 20 Jun. 2015 | ICTA-iRTG   | Outdoor     | 21 Jun. 2015 | 22 Sept. 2015 | ICTA-iRTG | Outdoor |
| <b>Average Temperature (°C)</b> | <b>16.5</b>  | <b>7.5</b>   | <b>21.6</b> | <b>16.7</b> | <b>25.9</b>  | <b>24.4</b>  | <b>18.8</b> | <b>13.1</b> |              |               |           |         |
| <b>Maximum Temperature (°C)</b> | 29.6         | 22.8         | 34.5        | 34.6        | 39.7         | 38.1         | 31.0        | 29.2        |              |               |           |         |
| <b>Minimum Temperature (°C)</b> | 6.3          | -3.6         | 13.5        | 1.2         | 15.7         | 11.8         | 10.2        | -2.3        |              |               |           |         |

437

438 During the coldest 2015 winter night when the temperature fell to -3.6°C, the corresponding iRTG  
 439 temperature (also its lowest recorded temperature) was 6.3°C. This is lower than the recommended value  
 440 of 14 °C, but higher, than the minimum winter night temperatures measured in conventional greenhouses  
 441 in the Mediterranean area (note that average iRTG winter temperatures are 9°C warmer than the average  
 442 external temperatures). This significant difference is due largely to the thermal inertia provided by the  
 443 concrete floor of the greenhouse and the use of the thermal screen and LDPE curtains at night, which  
 444 minimise thermal loss.

445 Conventional Mediterranean greenhouses do not commonly deploy heating [74], so the nocturnal  
446 temperatures in winter are usually the same or lower than those recorded outside [75,76]; this phenomenon  
447 does not occur in the iRTG. In this sense, the iRTG has a notable thermal advantage over the conventional  
448 greenhouses of the Mediterranean region during winter nights; this advantage translates into energy savings  
449 and better thermal conditions for crops in winter.

450 The iRTG weekly average summer temperature was 25.9 °C, with a maximum of 39.7°C (the outside  
451 weekly average and maximum were 24.4°C and 38.1°C, respectively). This is common in passive  
452 greenhouses in the Mediterranean region, due to the hot summers where mostly natural ventilation is used  
453 to dissipate the accumulated internal heat. As a last resort in passive greenhouses, shade nets are used to  
454 reduce the intensity of solar radiation received by the crop [26].

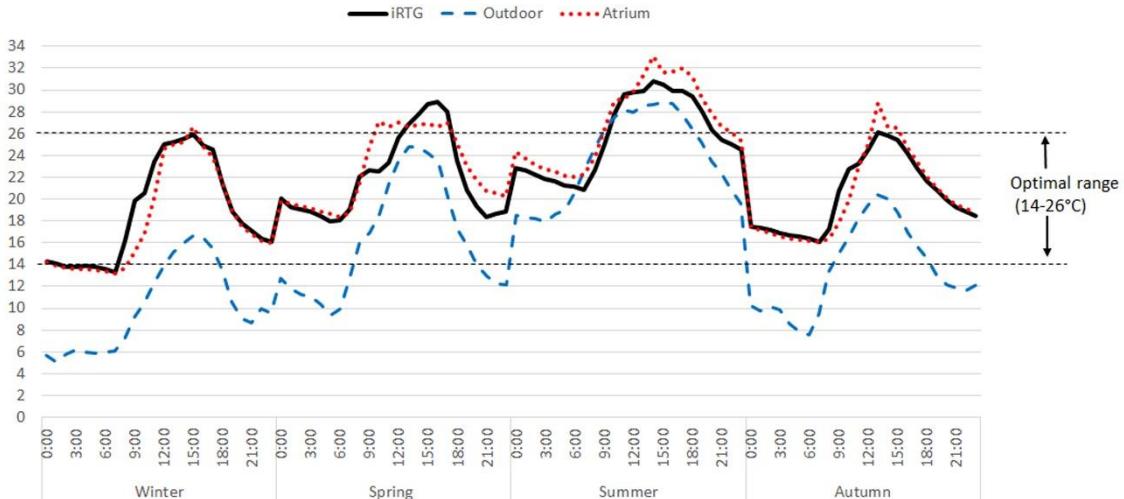
455 The risk of crop failure due to overheating ( $T_a > 40^\circ\text{C}$ ) could be mitigated through a rapid building control  
456 response to open greenhouse shutters for ventilation or closing the sun screen cover to reduce solar  
457 radiation. However, because of the integrated nature of the iRTG with the building, the thermal response  
458 would be slower. Therefore, given that 2015 was the first operational year, lack of experience with the  
459 controls meant that adapting to the outside weather conditions occasionally did not occur at the desired  
460 speed. The knowledge of the thermal behaviour of the iRTG gained during 2015 will be instrumental in  
461 solving the overheating challenge during its second operational summer (2016).

462 During spring and autumn, the iRTG had the most stable average temperatures (21.6 °C and 18.8°C,  
463 respectively), which are ideal for growing crops in Mediterranean areas. Despite having ideal thermal  
464 conditions, the intensity of solar radiation is not at its best, especially in autumn.

465

#### 466 **4.2 Annual thermal performance (4 seasons in 2015)**

467 To expand the scope of examination beyond the iRTG, it is necessary to explore the influence of the  
468 temperature of the rest of the building (common spaces without heating) on iRTG's thermal behaviour. Fig.  
469 5 outlines different average temperatures across 4 seasons during 2015 recorded in the iRTG, in common  
470 spaces without heating (atrium) and the outdoor temperature.



471

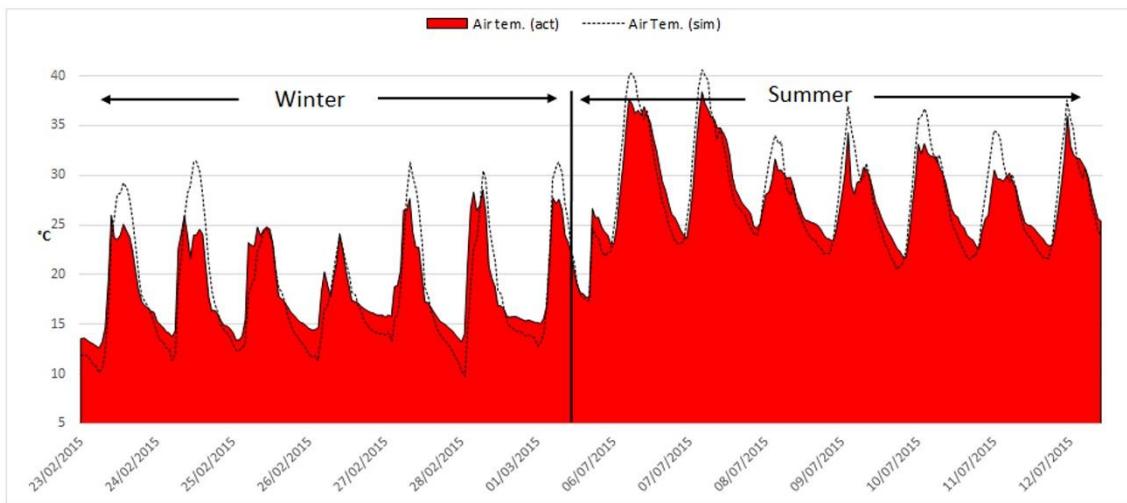
472 Fig. 5. Averaged hourly 2015 temperatures of 3 probe stations positioned inside the iRTG, the atrium and  
473 externally.

474 The 2015 thermal behaviour of the iRTG more closely resembles the atrium of the building than the outside  
475 conditions. Note that the atrium is open to the communal areas that are not conditioned. The conditioned  
476 offices and laboratories, however, interact with communal areas when doors and windows are left open.  
477 The greatest difference between the iRTG and the outside temperatures is in winter and autumn, due largely  
478 to the interaction between the building and the iRTG. The resulting 'elevated temperatures' in the iRTG  
479 offer an advantage over conventional greenhouses, which experience indoor temperatures sub-optimal for  
480 crop development during colder months.

481 **4.3 Model validation**

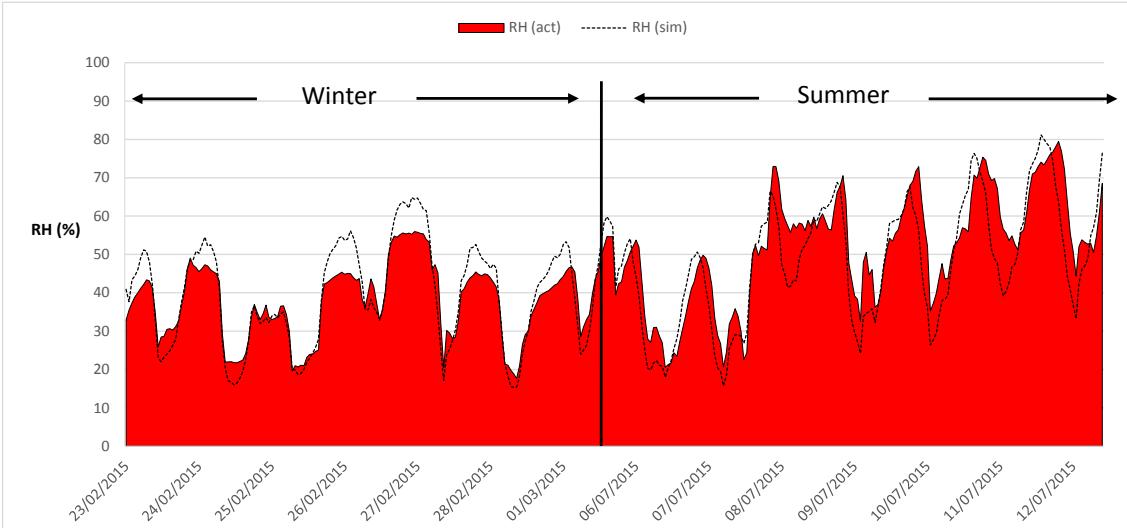
482 Figures 6 and 7 outline actual versus simulated hourly air temperature and humidity results for typical  
483 winter and summer weeks (using 2015 data) when the iRTG is modelled to replicate reality as a rooftop  
484 part of the ICTA-ICP building (Fig. 4-(a)). Respective MBE and CV(RMSE) values for air temperature are  
485 2.6% and 11.5% and for humidity are 2.9% and 15.9%; MBE figures provide an indication of errors  
486 averaged to the mean of the measured values, but they suffer from the cancellation effect. The CV (RMSE)  
487 index, however, 'accumulates' errors and normalises them to the mean of the measured values, which  
488 explains the difference in magnitude of the reported error indices. An error is defined as the actual value  
489 subtracted from the model prediction (i.e.,  $M_i - S_i$ ) [77]. Overall, the largest model errors occur in the daytime  
490 (7 am-6 pm) under clear sky conditions when internal temperatures are on average over-predicted by 5.4%.  
491 The second largest errors are, similarly, temperatures in the absence of solar irradiation (night values) that  
492 are on average under-predicted by 5.24%. This suggests that the actual iRTG internal climate is more  
493 moderate than the E+ model prediction. One explanation is that the ICTA laboratories discharge their

494 ‘closely controlled’ ventilation air into the iRTG. Recall from section 1-3 that the laboratory controls are  
 495 adjusted to achieve 21-25°C in an ad-hoc manner to satisfy the daily research agenda, and this ‘random’  
 496 discharge of ventilation air into the iRTG cannot be matched exactly by the deterministic control schedules  
 497 used in E+. In addition, researchers intervene to readjust the controls of the iRTG; that again departs from  
 498 the deterministic E+ schedules of the iRTG model. Nonetheless, both the temperature and humidity results  
 499 fall within ASHRAE guide 14 limits, and as per the concluding remarks of Royapoor et al. (2015), the  
 500 model can be considered validated.



501

502 Fig. 6. Hourly actual versus simulated air temperature results for the iRTG for winter and summer weeks.



503

504 Fig. 7. Hourly actual versus simulated humidity results for the iRTG for winter and summer weeks.

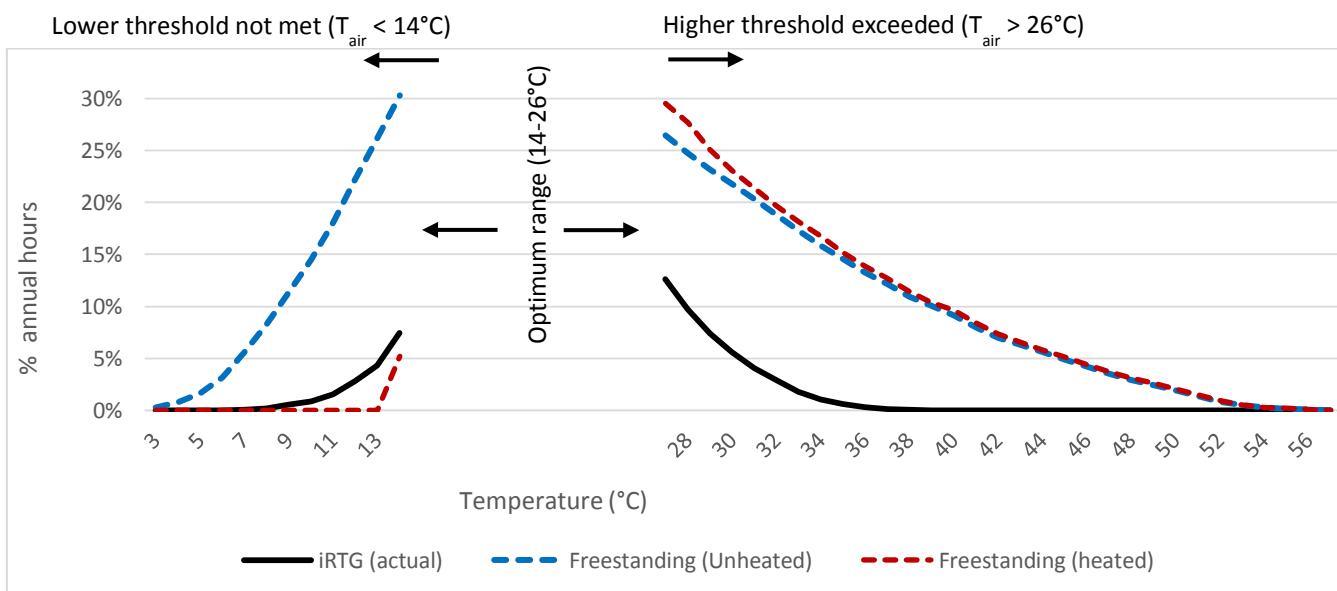
505

506 **4.4 iRTG in a free-standing condition**

507 This section reports the simulation results for an exact geometrical equivalent of the iRTG if it were a  
 508 freestanding structure erected on soil and independent from the ICTA building. In doing so, this section  
 509 first compares the annual indoor air temperatures of the actual iRTG with the freestanding model and  
 510 secondly reports the heating energy required to maintain the minimum 2015 air temperatures logged in the  
 511 actual iRTG.

512 Taking an optimum temperature range of 14-26 °C for the Mediterranean horticultural closed system  
 513 context, in 2015, the actual iRTG indoor climate met this condition in over 76.3% of annual hours. The  
 514 simulation result shows that under the same climatic conditions, an unheated freestanding structure identical  
 515 to the iRTG would have met the optimum range in only 42.4% of the annual hours; if heated, it would  
 516 satisfy the optimum range in 65.1% of annual hours (note that the heating target temperatures for the  
 517 freestanding model were actual hourly temperatures recorded in the iRTG during 2015). If model validation  
 518 errors are imposed on the results (i.e., correcting day over-predictions by -5.4% and night under-predictions  
 519 by +5.24%), the freestanding models meet the optimum range of 14-26°C for 47.5% and 66.3% of the  
 520 annual time in unheated and heated modes, respectively. This demonstrates that the error margins are too  
 521 small to alter the results in a dramatic way. Fig. 8 is a graph of instances when 14-26°C optimum range is  
 522 not met. As is evident, the freestanding greenhouse in both heated and unheated modes shows many more  
 523 instances of overheating in summer.

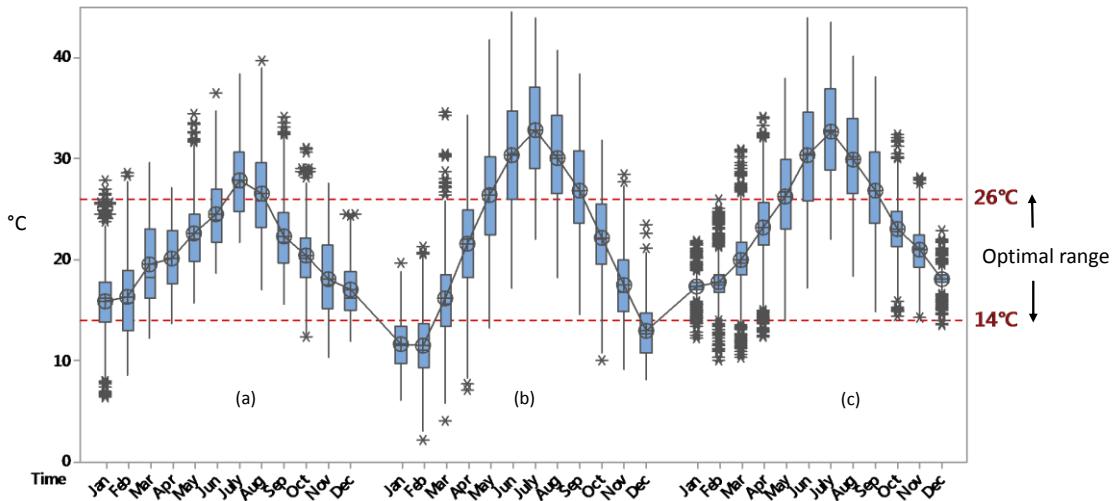
524



528

529 Fig. 8. % annual time with space air temperature falling outside the optimum range.

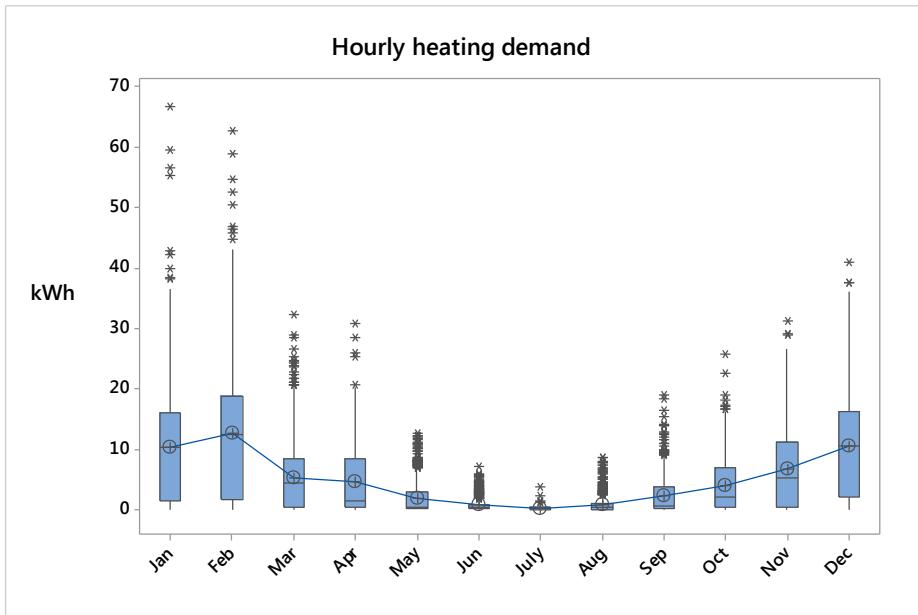
530 Therefore, the moderating effect that the integration of the iRTG with the building has had is not limited to  
531 higher winter temperatures. The actual iRTG has additionally not suffered as many instances of overheating  
532 that a freestanding structure would have experienced, thanks largely to the building thermal inertia and  
533 cooler exhaust air discharged into the iRTG in the summer. This is also evident from the plot of annual  
534 hourly temperatures (Fig. 9) in which the freestanding model would have had winter lows of 2°C in the  
535 unheated mode and summer highs of approximately 45°C in both modes (this occurs at times of high solar  
536 irradiance and high external temperatures).



537

538 Fig. 9. Hourly annual temperatures in (a) the actual iRTG (measured), (b) an unheated freestanding model  
539 of an iRTG (simulated) and (c) a heated freestanding model of an iRTG (simulated).

540 Fig. 10 is a plot of the hourly annual heating demand required to heat the freestanding model to achieve the  
541 minimum threshold temperatures recorded in the actual iRTG. Assuming a 100% fuel conversion  
542 efficiency, the total heating demand for the freestanding model would be 43.78 kWh under 2015 climatic  
543 conditions. This ideal heating requirement has a maximum of 66.62 kW with instances of heating required  
544 even in summer months (in early morning hours). This provides a scale of the total heating recycled by the  
545 actual iRTG from the ICTA-ICP building. Although the iRTG has also benefited from the summer cooling  
546 effect from the building, equivalent cooling loads were not calculated as this was deemed unrealistic in a  
547 commercial greenhouse context.



548

549 Fig. 10. Hourly annual heating requirements assuming 100% fuel conversion efficiency.

550

551 Maintaining a 100% energy-conversion efficiency, the simulation results were used to calculate the  
 552 financial and carbon savings of an iRTG relative to an equivalent heated greenhouse using associated  
 553 carbon intensities derived from regional sources [78–80]. The results show that an oil boiler meeting the  
 554 heating demands would produce 113.8 Kg.CO<sub>2(eq)</sub>/m<sup>2</sup>/yr, at a cost of 19.63 €/m<sup>2</sup>/yr. A gas boiler would  
 555 produce 82.4 Kg.CO<sub>2(eq)</sub>/m<sup>2</sup>/yr, costing 15.88 €/m<sup>2</sup>/yr; finally, a biomass boiler would result in 5.5  
 556 Kg.CO<sub>2(eq)</sub>/m<sup>2</sup>/yr at a cost of 17.33 €/m<sup>2</sup>/yr.

557 These economic and CO<sub>2</sub> savings demonstrate the feasibility of integrating greenhouses into buildings as a  
 558 new strategy, forming a resilient and low-carbon civic infrastructure in which the capacity to meet urban  
 559 food supplies exists locally, supporting food security and sovereignty of the most vulnerable sectors of the  
 560 urban population. In doing so, the traditional idea of urban zones with inadequate green areas can be  
 561 challenged because even when substantial concrete and masonry building surfaces exist, it is possible to re-  
 562 function under-utilised rooftops for the cultivation of various fruits and vegetables in cities around the  
 563 world, particularly in cities with growing populations, a lack of space for growth, a very large constructed  
 564 area and a high dependence on importing vegetables, such as Shanghai, Beijing and Guangzhou in China  
 565 and several cities in the USA, Japan and Canada.

566  
567

## 5 Conclusions and future work

568 The urgency to reduce the environmental impact of civic life requires solutions that achieve greater  
569 efficiencies, in particular, by minimising waste and maximising the use of finite resources. The energy-  
570 intensive nature of agriculture and the built environment offers opportunities in which an integrated  
571 approach can lead to more efficient resource management. An iRTG at the ICTA-ICP building within the  
572 UAB university campus demonstrated an ideal closed system greenhouse facility in which (its first  
573 operational year) 16.2 kg/m<sup>2</sup> of *cor de bou* tomato and two successive crops of lettuce were produced in  
574 2015. A validated model demonstrated that the integrated nature of the iRTG resulted in 341.93 kWh/m<sup>2</sup>/yr  
575 of heating energy being ‘recycled’ from the rest of ICTA building; this is within 139–444 kWh/m<sup>2</sup>/yr of  
576 the reported power requirements for heated Mediterranean greenhouses. Although the iRTG is not actively  
577 conditioned and has a transparent fabric, its internal temperatures are greatly stabilised through thermal  
578 ‘coupling’ with the rest of the ICTA building. This was evident as the actual recorded air temperatures  
579 within the iRTG were much closer to the recorded building thermal mass and indoor air temperatures than  
580 to the external climatic conditions. Validated simulation results also showed that under the same climatic  
581 conditions and control regimes, instances of ‘sub-optimal’ temperatures (outside the 14–26°C range) would  
582 have been 33.5% higher in a freestanding greenhouse (in the form of low winter and excessive summer  
583 temperatures). Eliminating limited instances of summer overheating altogether remains the main challenge  
584 for the iRTG research team; this highlights the need for detailed planning at the design stage and consistent  
585 monitoring after commissioning if similar building-integrated greenhouses are inaugurated elsewhere.  
586 While the empirical foundation of this paper relies on data from Southern Europe and specifically a  
587 Mediterranean context, the validated results offer a broader scope. Archetypes of buildings and climatic  
588 variations across the world can be exploited to enable building-integrated greenhouses to function  
589 adequately, and as such, pilot projects to verify the socio-economic and energy benefits of greenhouse  
590 integration in the urban space remain invaluable. At the same time, major conurbations across the U.S.  
591 (California in particular), southern Chile, Cape Province in South Africa, and the southwest of Australia all  
592 share ecosystem characteristics similar to the Mediterranean area in which the iRTG has been demonstrated  
593 as a viable concept. Future research will focus on the characterisation of bidirectional energy performance  
594 between the greenhouse and the building to quantify potential heating energy savings in the ICTA-ICP  
595 building derived from the rooftop greenhouse and to analyse the implementation of the iRTG concept in  
596 different geographical areas of the world where urban agriculture and improved energy efficiency in the  
597 built environment can be combined.

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 601 Technology, State of Yucatan (CONCIYTEY) for awarding a research scholarship to Ana Nadal and the  
 602 Spanish Ministerio de Economía y Competitividad (MINECO) for financial support to the research project  
 603 “Agrourban sustainability through rooftop greenhouses. Ecoinnovation on residual flows of energy, water  
 604 and CO<sub>2</sub> for food production” (CTM2013-47067-C2-1-R). The authors appreciate the technical help of  
 605 Carla Planas (Group of Construction Research and Innovation (GRIC), Department of Projects and  
 606 Construction Engineering, Universitat Politècnica de Catalunya-BarcelonaTech).

607 **Appendix**

608 Table A1: Thermo-physical and surface properties of the fabric construction of the ICTA-iRTG model.

609

|                                     |  |                      |
|-------------------------------------|--|----------------------|
| Clear Polycarbonate fabric material | Thickness (mm)   | 0.8 <sup>[1]</sup>   |
|                                     | Conductivity (W/mK)  | 0.2 <sup>[1]</sup>   |
|                                     | Solar transmittance  | 0.835 <sup>[1]</sup> |
|                                     | External surface solar reflectance                                 | 0.075 <sup>[2]</sup> |
|                                     | Internal surface solar reflectance                                 | 0.075 <sup>[2]</sup> |
|                                     | Visible light transmittance  | 0.883 <sup>[1]</sup> |
|                                     | External visible light reflectance                                 | 0.061 <sup>[2]</sup> |
|                                     | Internal visible light reflectance                                 | 0.060 <sup>[2]</sup> |
|                                     | Total Infrared transmittance                                       | 0.800 <sup>[1]</sup> |
|                                     | External surface emissivity (IR)                                   | 0.900 <sup>[2]</sup> |
|                                     | Internal Surface emissivity (IR)                                   | 0.900 <sup>[2]</sup> |
| Galvanised Steel framing            | U-value (W/m <sup>2</sup> K)                                       | 5.7 <sup>[1]</sup>   |
|                                     | Thickness (mm)   | 4 <sup>[1]</sup>     |
|                                     | Inside convective heat transfer coefficient (W/m <sup>2</sup> K)   | TARP <sup>[6]</sup>  |
|                                     | Internal radiative heat transfer coefficient (W/m <sup>2</sup> K)  | 1.847 <sup>[2]</sup> |
|                                     | External surface resistance (m <sup>2</sup> K/W)                   | 0.135 <sup>[2]</sup> |
|                                     | External convective heat transfer coefficient (W/m <sup>2</sup> K) | DOE-2 <sup>[6]</sup> |
|                                     | External radiative heat transfer coefficient (W/m <sup>2</sup> K)  | 1.71 <sup>[2]</sup>  |
| High-Density Polyethylene           | Surface resistance (m <sup>2</sup> K/W)                            | 0.04 <sup>[2]</sup>  |
|                                     | U-value (W/m <sup>2</sup> K)                                       | 5.84 <sup>[2]</sup>  |
|                                     | Thickness (mm)   | 0.65                 |
|                                     | Thermal conductivity (W/m.K)                                       | 0.5                  |
| Floor cover                         | Specific heat (J/Kg.K)   | 1800                 |
|                                     | Density (Kg/m <sup>2</sup> )                                       | 980                  |

|                                       |   |                     |
|---------------------------------------|---|---------------------|
| Partition<br>Polyethylene<br>Curtains | Surface thermal absorbance  | 0.9                 |
|                                       | Surface solar absorbance  | 0.7                 |
|                                       | Internal Convective heat transfer coefficient<br>(W/m <sup>2</sup> K) | 11.54               |
|                                       | U-value (W/m <sup>2</sup> K)  | 2.45                |
| Soil Condition <sup>[5]</sup>         | Emissivity  | 0.69 <sup>[1]</sup> |
|                                       | Transmissivity  | 0.19 <sup>[1]</sup> |
|                                       | Reflectivity  | 0.12 <sup>[1]</sup> |
| Other                                 | Active thickness (mm)   | 490                 |
|                                       | Conductivity (W/m.K)  | 1.28                |
|                                       | Specific heat (J/Kg.K)  | 880                 |
|                                       | Density (Kg/m <sup>2</sup> )  | 1460                |
|                                       | Thermal absorbance  | 0.9                 |
|                                       | Solar absorbance  | 0.7                 |
|                                       | Vapour resistivity (MNs/g)  | 10                  |
|                                       | U-value (W/m <sup>2</sup> K)  | 2.45                |
| Footnotes:                            | Lighting (W/m <sup>2</sup> )  | 3 <sup>[3]</sup>    |
|                                       | Occupant Density (people/m <sup>2</sup> )                             | 0.6 <sup>[4]</sup>  |
|                                       | Discharge coefficient for openable windows                            | 0.65                |

[1]

Manufacturers product technical literature

[2]

Cambridge University CES EduPack 2015 database (reference data)

[3]

6x T5 Fluorescents (60 W each) over a total area of 142 m<sup>2</sup>

[4]

A total of 30 half hourly visits by 3 to 5 researchers at various office hours

[5]

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[6]

See method section

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