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AN INTEGRATED ENERGY AND BIOCLIMATIC SYSTEM FOR POSITIVE-ENERGY BUILDINGS: BIPV, ELECTRICAL STORAGE AND A ROOFTOP GREENHOUSE

Research paper

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Abstract: Highly insulated and airtight buildings reduce the heating demand, but they also retain indoors the carbon dioxide exhaled by the occupants and, in most cases, they remain simple consumers of energy. This paper proposes an integrated energy and bioclimatic system in which the envelope of a public building produces electricity through building-integrated photovoltaics (BIPV), a battery shifts this production towards the evening hours, and a rooftop bioclimatic greenhouse is coupled to the ventilation circuit so that the plants remove a part of the carbon dioxide generated indoors. A reduced-order model of the coupled building–greenhouse–photovoltaic–storage system is formulated and a preliminary annual assessment is carried out for a 600 m² office building located in Arad, western Romania. The estimated results indicate an annual energy balance ratio of 1.41, a self-sufficiency of 82% obtained with a 60 kWh battery, an indoor carbon dioxide concentration kept below 1000 ppm during the occupied period with a fresh-air flow rate reduced by 27%, and approximately 17.7 t of avoided carbon dioxide emissions per year. The paper also defines the modelling and experimental programme of ongoing doctoral research.
Key words: *BIPV, positive-energy building, energy storage, indoor air quality, rooftop greenhouse*

INTRODUCTION

The building sector is one of the main targets of the European climate policy, and photovoltaic technology is expected to provide a large share of the required on-site generation (Kougias et al., 2021). Building-integrated photovoltaics (BIPV) extend this role from the roof to the whole envelope, the modules being used at the same time as generation units and as construction elements (Biyik et al., 2017). When the photovoltaic generator is combined with electrical storage, the share of the production that is consumed on site increases substantially, typically by 13–24 percentage points for a storage capacity of 0.5–1 kWh per installed kW (Luthander et al., 2015).

At the same time, the thermal renovation of buildings has a less visible consequence. A well-insulated and airtight envelope reduces the uncontrolled air exchange, so the carbon dioxide exhaled by the occupants accumulates in the occupied rooms. Concentrations that are commonly reached in meeting rooms and classrooms have been associated with a measurable decrease of the higher-order cognitive function of office workers (Allen et al., 2016), and the reference indoor air quality categories of EN 16798-1 are defined precisely through the carbon dioxide concentration above the outdoor level (European Committee for Standardization, 2019). The conventional answer is dilution ventilation, which consumes in winter a part of the energy saved through insulation.

A third line of research, apparently unrelated, is the integration of agriculture into the building. The integrated rooftop greenhouse built on the ICTA-ICP building in Barcelona demonstrated that heat, carbon dioxide and rainwater can be exchanged between a building and the greenhouse placed on its roof, with a better environmental performance than that of a free-standing greenhouse (Nadal et al., 2017)

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The three directions are usually treated separately: the photovoltaic generator is sized by the electrical engineer, the ventilation system by the mechanical engineer and the greenhouse, when it exists, by the horticulturist. The optimum of each subsystem taken separately is not the optimum of the assembly. The aim of this paper is to describe a system in which the three subsystems are coupled and operated by a single supervisory controller, to formulate a reduced-order model suitable for control design, and to present a preliminary estimate of the energy, indoor air quality and environmental performance for a case study located in the temperate continental climate of western Romania. The work is the starting point of a doctoral research programme and continues the previous analyses of residential photovoltaic systems of the authors (Petcuț-Lasc et al., 2024).
The main contribution of this work is the integrated formulation of BIPV generation, electrical storage, indoor CO_2 management and rooftop greenhouse operation within a unified supervisory control framework for positive-energy public buildings.

THE PROPOSED SYSTEM

The structure of the proposed system is presented in Fig. 1. It contains four subsystems and two coupling loops.

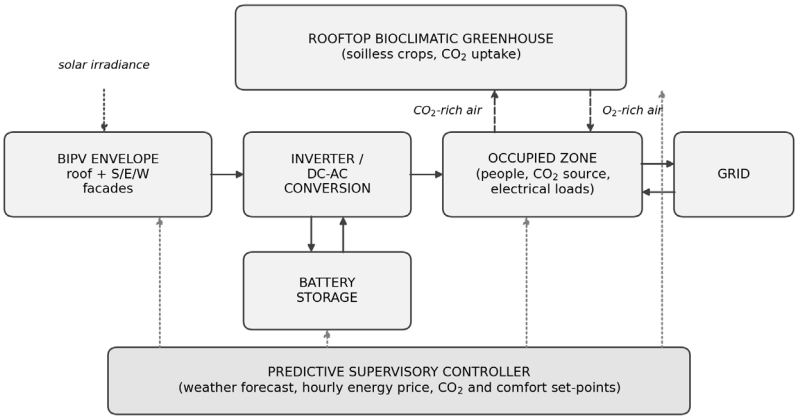


Fig. 1. *Structure of the integrated energy and bioclimatic system*

The generation subsystem consists of photovoltaic modules integrated in the roof and in the south, east and west façades. The façade modules produce less energy in summer, when the sun is high, but they compensate a part of the winter deficit, when the sun is low and the days are short, so the annual production profile becomes flatter than that of a roof-only installation.
The storage subsystem is a lithium-iron-phosphate battery. Its role is not to increase the annual production, but to move it in time: the maximum production occurs around noon, while the building consumes mainly in the morning and in the evening.
The bioclimatic subsystem is a soilless greenhouse placed on the roof. The air of the occupied zone, enriched in carbon dioxide, is transferred to the greenhouse, where a part of the carbon dioxide is consumed by photosynthesis, and the air returned to the occupied zone has a lower carbon dioxide concentration. The greenhouse therefore acts as a partial regeneration stage of the indoor air and, at the same time, as a thermal buffer above the last floor and as a source of fresh vegetables.
The fourth subsystem is the supervisory controller. It receives the weather forecast, the hourly energy price and the measured states of the building, and it computes the air flow rates, the charging and discharging power of the battery and the set-points of the heat pump. The natural formulation for such a multi-objective problem is model predictive control, whose application to buildings is now well documented (Drgoňa et al., 2020).

MATERIAL AND METHODS

Reduced-order model

The model used for control design is a lumped-parameter model. The carbon dioxide balance of the occupied zone, whose air volume is V_z and whose concentration is C_z, is written as:

$$V_z \frac{dC_z}{dt} = nG_p + q_v(C_g - C_z) \quad (1)$$

where n is the number of occupants, G_p is the carbon dioxide generation rate per person, q_v is the air flow rate exchanged with the greenhouse and C_g is the concentration in the greenhouse. The balance of the greenhouse, of volume V_g, contains in addition the infiltration term and the photosynthetic uptake:

$$V_g \frac{dC_g}{dt} = q_v(C_z - C_g) + q_i(C_o - C_g) - \Phi_p \quad (2)$$

in which q_i is the infiltration flow rate, C_o is the outdoor concentration and Φ_p is the net carbon dioxide uptake of the crop, which depends on the photosynthetically active radiation, on the leaf area and on the concentration itself. For this preliminary assessment, the photosynthetic CO_2 uptake was represented by a simplified constant uptake rate per unit leaf area. This assumption will be replaced by an experimentally identified radiation and CO_2 dependent model in the subsequent stage of the research. A net uptake rate of 5 μmol CO_2 m^{-2} s^{-1} of leaf area was applied during daylight hours, together with a leaf area index of 2.5, i.e. about 375 m² of leaf area for the 150 m² greenhouse (Table 1). The value is well below the light-saturated leaf photosynthesis rates reported for greenhouse vegetable crops (Marcelis et al., 1998) and was chosen conservatively to account for the low winter irradiance; it corresponds to about 0.3 kg of CO_2 per hour, i.e. roughly one fifth of the CO_2 generated by the 40 occupants. The state of charge of the battery follows the usual relation:

$$E_b \frac{dSOC}{dt} = \eta_c P_{ch} - \frac{P_{dis}}{\eta_d} \quad (3)$$

where E_b is the usable capacity of the battery and η_c and η_d are the charging and discharging efficiencies. Two indicators are used for the annual assessment: the energy balance ratio *EBR*, defined as the ratio between the on-site production E_{PV} and the electricity demand E_L, and the self-sufficiency *SS*, defined with the energy imported from the grid E_{imp}:

$$EBR = \frac{E_{PV}}{E_L} \quad , \quad SS = 1 - \frac{E_{imp}}{E_L} \quad (4)$$

Case study and assumptions

The reference object is an existing office building located in Arad, in the west of Romania, in a temperate continental climate. The hourly production of the photovoltaic generator was estimated for each orientation from a typical meteorological year, and the electrical demand was built from the measured load profile of a similar administrative building. The main assumptions are given in Table 1.

The typical meteorological year (TMY) used to estimate the hourly photovoltaic production was obtained from the PVGIS (Photovoltaic Geographical Information System) database, developed by the Joint Research Centre of the European Commission, for the site of Arad, Romania (46.18° N, 21.31° E). The TMY dataset, derived from multi-year climatological series

(reference period 2005–2020, depending on the SARAH-3/ERA5 solar-radiation database selected in PVGIS) following the Sandia/ISO 15927-4 methodology, provides hourly values of global horizontal and tilted irradiance, air temperature and wind speed that are statistically representative of an average climatic year rather than of an extreme year. The production of each orientation of the photovoltaic generator (roof, south façade, east and west façades) was estimated separately, applying the tilt and azimuth angles corresponding to the BIPV configuration described in the previous section, using the conversion model integrated in PVGIS (the PVGIS-CM SAF irradiance model together with the Faiman cell-temperature model).

Table 1. *Main parameters of the case study*

Parameter	**Value**
Useful floor area / occupants	600 m² / 40 persons
Occupancy schedule	08:00–18:00, working days
Annual electricity demand	34 000 kWh
BIPV roof, 30° south	28 kWp
BIPV south façade	10 kWp
BIPV east and west façades	2 × 6 kWp
Battery capacity / round-trip efficiency	60 kWh / 92 %
Greenhouse area / air volume	150 m² / 450 m³
Air flow rate between zone and greenhouse	max. 2 000 m³/h
CO_2 generation rate per person	18 l/h
Outdoor CO_2 concentration	420 ppm
Grid emission factor	0.37 kg CO_2/kWh
Leaf area index / net CO_2 uptake of the crop	2.5 / 5 μmol m^{-2} s^{-1} (daytime)

RESULTS AND DISCUSSION

The estimated monthly electricity production and consumption are presented in Fig. 2. The annual production is 47 900 kWh, for an annual demand of 34 000 kWh, which corresponds to an energy balance ratio of 1.41. During eight months of the year, from March to October, the building delivers to the grid more energy than it takes from it; the deficit remains concentrated in the four cold months, when the heating demand is maximum and the solar resource is minimum.

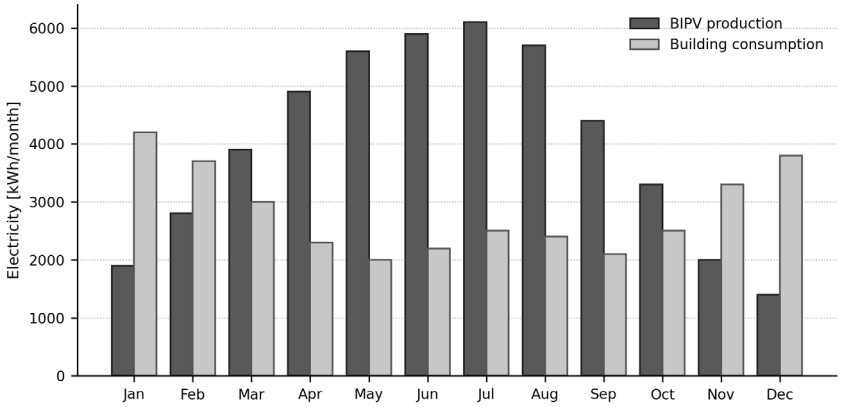


Fig. 2. *Estimated monthly electricity production and consumption*

Through the direct consumption of the photovoltaic production and the battery of 60 kWh, which shifts a part of the midday surplus towards the morning and evening hours, about 27

900 kWh per year are covered on site, so the self-sufficiency computed with relation (4) reaches 82 %, and the energy imported from the grid falls to 6 100 kWh per year. The surplus of approximately 20 000 kWh delivered to the grid is comparable with the annual consumption of ten average households.
The effect of the greenhouse loop on the indoor air quality is shown in Fig. 3, for a typical winter working day. In the reference case, with the windows closed and with the minimum mechanical ventilation, the concentration exceeds 1400 ppm after about four hours of occupancy. When a part of the air is circulated through the greenhouse, the concentration remains below 1000 ppm, which corresponds to category II of EN 16798-1, while the fresh-air flow rate taken from outside, and implicitly the energy needed to heat it, is reduced by 27 %.

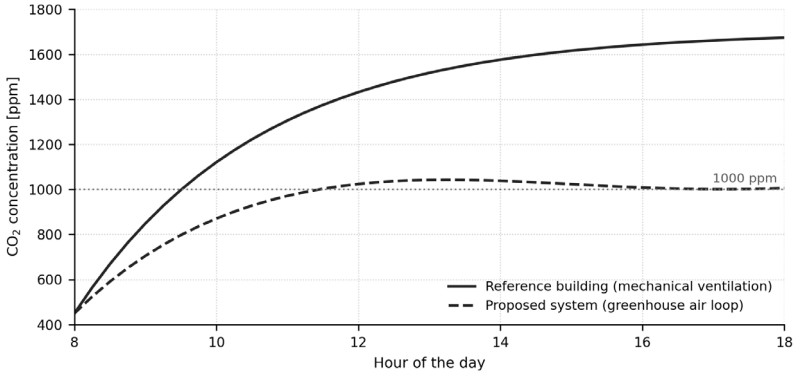


Fig. 3. *Indoor CO_2 concentration during a typical winter working day*

The comparison between the reference building and the proposed system is summarised in Table 2. Besides the energy and air quality indicators, the greenhouse produces about 3.5 t of vegetables and herbs per year on 150 m² of soilless culture, and the avoided emissions, computed with the emission factor of the Romanian grid, are of the order of 17.7 t of carbon dioxide per year.

Table 2. *Estimated annual performance, reference building and proposed system*

Indicator	Reference building	Proposed system
Electricity demand	34 000 kWh	34 000 kWh
On-site production	–	47 900 kWh
Energy balance ratio	0	1.41
Self-sufficiency	0 %	82 %
Energy imported from the grid	34 000 kWh	6 100 kWh
Energy delivered to the grid	–	20 000 kWh
Peak indoor CO_2 concentration	1 400–1 800 ppm	below 1 000 ppm
Fresh air taken from outside	reference	−27 %
Vegetables produced	–	≈ 3.5 t/year
Avoided CO_2 emissions	–	17.7 t/year

For public buildings such as schools, town halls or hospitals, the high self-sufficiency means a lower exposure to electricity price increases; a detailed economic assessment, based on actual investment costs, will be carried out in a subsequent stage of the research.

Sensitivity analysis

To assess the robustness of the preliminary results with respect to the sizing assumptions, a sensitivity analysis was performed for two parameters considered critical for the energy performance of the system: the usable battery capacity (E_b) and the annual electricity demand

(E_L). The analysis was carried out by deterministic simulation, keeping all other assumptions of Table 1 unchanged. The analysis focused on the energy balance ratio (*EBR*), while the influence of battery capacity on self-sufficiency will be quantified in a subsequent stage using the complete hourly model. Two levels were considered for the battery capacity, 40 kWh and 80 kWh, corresponding to approximately ±33% relative to the reference case and reflecting the usual commercial range of lithium-iron-phosphate modules available for a building of this size, together with a variation of ±10% in the annual electricity demand. Each scenario was obtained from a single simulation run, keeping the remaining parameters fixed (a one-factor-at-a-time design); a full factorial sensitivity analysis is left for a later stage of the research. The results are summarised in Table 3.

Table 3. *Sensitivity of the annual performance indicators to battery capacity and electricity demand*

Scenario	Battery (kWh)	Demand (kWh/year)	EBR
Reference	60	34 000	1.41
Battery −33%	40	34 000	1.41
Battery +33%	80	34 000	1.41
Demand +10%	60	37 400	1.28
Demand −10%	60	30 600	1.57

The results indicate that the energy balance ratio remains unchanged with the battery capacity, since this indicator depends only on the annual production and demand and not on the temporal distribution of the energy, and that it is, as expected, sensitive to the electricity demand, a variation of ±10% shifting it from 1.28 to 1.57. The battery capacity, by contrast, is expected to mainly affect the self-sufficiency rather than the energy balance ratio, consistent with the role of the battery as a means of shifting the energy in time rather than increasing its production, as stated in the "THE PROPOSED SYSTEM" section; quantifying this effect requires re-running the hourly model for each battery scenario and is left for a further stage of the analysis.

The results presented here are preliminary and have the value of an order of magnitude. They were obtained with a lumped-parameter model, with a constant photosynthetic uptake per unit of leaf area and with a perfect forecast of the weather and of the load. The main uncertainties concern the real uptake of the crop under variable radiation, the acceptance of a partially recirculated air by the occupants, and the behavior of the greenhouse during the summer, when it has to be protected against overheating. These aspects can be settled only by measurement, which is the reason for which the experimental validation is a central part of the research program.

CONCLUSION

The paper proposed an integrated energy and bioclimatic system in which the photovoltaic envelope, the electrical storage and a rooftop greenhouse are operated together, by a single supervisory controller, instead of being designed and operated separately. A reduced-order model of the coupled system was formulated, and a preliminary annual assessment was carried out for an office building located in western Romania.

The preliminary results suggest that the three objectives can be simultaneously pursued within the proposed integrated system: the building can produce about 41 % more electricity than it consumes over a year, it can cover 82 % of its own demand with a moderate battery, and it can keep the indoor carbon dioxide concentration below 1000 ppm with a fresh-air flow rate reduced by 27 %, while also producing fresh vegetables on the same surface.

The next stages of the research are the identification of the model parameters on measured data, the formulation of a simultaneous sizing methodology for the photovoltaic generator and the storage, and the construction of an instrumented demonstrator monitored over twelve months, so that the results are obtained in a temperate continental climate and not transferred

from the Mediterranean or northern European literature. The final objective is not a theoretical study, but a verified design methodology, applicable to the public buildings that are currently being renovated.

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