Energy & Buildings 285 (2023) 112891

Contents lists available at ScienceDirect

Energy & Buildings

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

Solar energy engineering and solar system integration – The solar Decathlon Europe 21/22 student competition experiences

Karsten Voss [a,*], Isil Kalpkirmaz Rizaoglu [a], Andrea Balcerzak [a], Heiko Hansen [b]

[a] School of Architecture and Civil Engineering, University of Wuppertal, Pauluskirchstrasse, 7, D-42285 Wuppertal, Germany
[b] Hansen + Partner Ingenieure GmbH, Lise-Meitner-Str. 1-3, D-42119 Wuppertal, Germany

ARTICLE INFO

Article history:
Received 5 December 2022
Revised 7 February 2023
Accepted 10 February 2023
Available online 15 February 2023

Keywords:
Building competition
Teaching
Solar buildings
Photovoltaics
Building grid interaction
Solar system integration

ABSTRACT

The Solar Decathlon is a competition for universities from all over the world which focuses on designing, building and operating experimental, solar-powered houses. Participating in the project offers universities a unique and interdisciplinary platform for teaching, learning and research which combines practical experience with research. In 2022, the European edition was held in Germany for the first time. The event took place with a new urban profile to increase both the relevance of the competition and the learning experience. Its main topic was the further development of the European city, and specifically focused on the existing stock of residential apartment buildings. A total of 18 teams from 11 countries with over 500 students took part, with 16 teams ultimately building their houses on a shared solar campus. Demonstrating a balanced or a positive energy balance in practice was one of the essential goals of the competition. This was achieved by 13 of 15 projects in the energy contest. The prerequisites for this were a high level of energy efficiency and the consistent use of solar energy. Both strategies were embedded in convincing architectural concepts. These ranged from the minimised visibility of standard systems on rooftops, through to custom-built systems with full architectural integration in façades. Hybrid solar systems also became a focus, with the goal of making optimum use of the surfaces on the building envelope. This paper focuses on the energy engineering and technical and architectural integration of the solar systems. It also includes the results achieved in the competition linked to the learning experience.

1. Introduction

The Solar Decathlon (SD) is a university-level building competition with a history which stretches back more than 20 years. Its first edition took place in the US in 2002 [1]. During the competition, students are challenged to design, build, and operate small, high-performance solar building prototypes. The final phase consists of assembling the houses on a common site where all the prototypes are exhibited and compete, passing through ten different contests that make up the competition (the decathlon). The main objectives of the SD are to educate the next generation of architects and engineers and to inspire the public, making them aware of the efficient use of resources as well as the carbon–neutral building energy supply, namely through building integrated solar systems and through ambient energy utilization. After initial editions with off-grid, energy autonomous houses, the subsequent competitions have focused on "net zero energy solar buildings" as well as "net energy positive buildings" operating in connection with the power grid. According to [2], a *net zero* energy building is "conceptually understood as an energy efficient building that balances its energy demand on an annual basis by generating electricity, as well as thermal energy carriers, from renewable sources". We can certainly say that today's situation is completely new. The costs of fossil energy are increasing substantially. The costs of solar power generation have decreased so much that it has become the most affordable form of energy production along with hydro and wind energy. The technical and architectural integration of these possibilities is a pressing issue, particularly in the case of existing buildings. For a long time, this was considered a purely theoretical option; it is now becoming pretty much compulsory in Europe.

The SD addresses students as its main stakeholders and beneficiaries. The participating universities create an outstanding educational opportunity in an international network. In many cases, the work on the competition becomes part of the teaching in courses such as architecture, civil, mechanical- and electrical engineering as well as design. It creates the basis for learning which is close to research as well as practice, and for interdisciplinary teaching across faculties [3]. The organisers of the SD have created educational material specialised for different target groups and levels

---

[*] Corresponding author.
E-mail address: kvoss@uni-wuppertal.de (K. Voss).

https://doi.org/10.1016/j.enbuild.2023.112891
0378-7788/

[4,5]. Based on the results of a world-wide survey among participants it was concluded from approximately 400 responses "... that the vast majority of respondents were satisfied with the competition, would recommend it to others, and would repeat the experience" [6].

Although driven by universities, the SD is not a research project. On the one hand, different buildings are created around a common theme and evaluated under comparable conditions on a common site. On the other hand, only the smaller part of these comparisons are based on engineering methods, while the majority are based on jury judgements. Due to the measurements over a comparatively short period of time, the limited monitoring equipment and the character as a public outdoor event outside the heating season, the analyses of the measurement data focus on selected areas only and are mostly not scalable to an annual performance perspective. Beyond that, however, the comparative consideration of strategies and system concepts lends itself as an approach. Earlier cross-sectional analyses of this kind addressed, for example, general technological innovation [7,8], phase change materials [9], HVAC technologies [10], solar systems [11] and energy concepts [12]. Apart from the joint event, the participation in the competition offers the university teams a platform for their own research relating to the profile of the participating faculties and in contact with businesses. Examples for such activities are reported in 17 research articles in the special issue of Energy and Buildings, "Science behind and beyond the Solar Decathlon Europe 2012" [13]. The advantage of this individual research is that the buildings are still available after the competition, usually at the home location of the university.

The objective of the paper is to investigate the performance of the buildings with respect to solar energy and disciplines relating to architectural engineering, combined with the associated learning experiences. After describing the new profile of the 21/22 SD edition (chapter 2), the general properties of the 16 buildings in competition are presented (chapter 3), and the monitoring and testing is described (chapter 4). The core topics of the paper are the energy performance analysis based on monitored data (chapter 5) and the comparative consideration of the architectural and technical integration of solar systems (chapter 6), before concluding with lessons learned and an outlook (chapter 7 and 8).

In addition to this paper, a comprehensive open source "competition source book" summarises the event, the results and the teams' contributions in further detail [14]. Another paper compiles the results and experiences relating to the building physics [15]. Additionally, an interactive 3D tour for all buildings is available on the event website to experience the exterior and interior architecture [16]. The building tasks, the competition rules and all the buildings and monitored data are documented on the "competition knowledge platform" of the Energy in Buildings and Communities Programme (EBC) of the International Energy Agency (IEA) for intensive post competition usage in research and education [17,5]. From spring 2023, eight remaining buildings will be reopened to visitors as part of a follow-up living lab project [18].

2. Solar Decathlon Europe 21/22 goes urban

In its 4th European edition, the event was held in Germany for the first time. The final was originally scheduled to take place in autumn 2021, but was moved to spring 2022 due to the worldwide pandemic.

The Solar Decathlon Europe 21/22 (SDE 21/22) was the first edition to be inspired by the work and outcome of the IEA EBC Annex 74 "Competition and Living Lab Platform" [17]. Based on the findings, the SDE 21/22 included new elements to inspire post competition analysis in selected areas of research. With respect to energy engineering these were, namely:

- a consistent documentation of key project facts and indicators in a comparable set of data sheets per project to improve the comparability
- a consistent separation of the monitoring and visiting times to increase the usability of the monitoring data
- blower door (chapter 4.3) and co-heating tests (chapter 4.4) for the characterisation of the thermal building properties under comparable conditions
- the use of a simplified dynamic simulation tool to estimate the thermal building performance on a common platform (chapter 4.4)
- a modified contest for testing the building energy flexibility in the interaction with the power grid to better reflect the needs of power grids with a high penetration of fluctuating power from renewables (chapter 5.3)
- an extended monitoring system to quantify the performance of the PV system (chapter 6.2).

The SDE 21/22 was held with a new urban profile to increase both the competition's relevance and the learning experience. Its key topic was the further development of the European city, and specifically focused on the existing stock of residential apartment buildings. The specific tasks were vertical and horizontal extensions of existing buildings and closing gaps between buildings, consistently taking the architectural and technical improvement of the existing parts of the buildings into account. This urban profile of the competition finds detailed reflection in the ten disciplines (Table 1) and the new competition rules [16]. Holding the competition in Germany formed part of Germany's efforts to achieve a climate-neutral building stock by 2045 with its Climate Chance Act 2021 [19]. This was also the reason for the funding that was provided by the German Federal Ministry of Economic Affairs and Climate Action.

The course of the new competition format involves two challenges for the student teams (Fig. 1, Fig. 2, Table 1):

- In the "Design Challenge", the teams create a design and energy concept for the renovation and extension of an existing building (or an urban gap), including its urban context, bringing principles of climate neutrality together.
- In the "Building Challenge", the teams construct a representative full-scale House Demonstration Unit (HDU) for the event site in Wuppertal. The results are fully functional, one to two-storey apartments with up to 110 m^2 of living space. While the teams are free to choose the most representative part of their building design, the solar systems must also be included.

After two weeks of thrilling assembly activities, 16 university teams demonstrated their work on a common solar campus. Three strategies formed the focus of all the teams – which have always been part of basic practice in the sustainable economy: sufficiency, efficiency and consistency. In other words, reducing the amount of living space per person, frugality regarding the use of energy and resources, and the consistent recirculation of the materials and products used. More than 115,000 visitors went to see the campus in June 2022. They were inspired by the ideas and positive energy of the 500 young, international students. Despite the circumstances of the competition, cooperation and teamwork proved to be the perceptible spirit of this SDE edition. This spirit underlines the power of international cooperation for successfully rising to the ecological and economic challenges of the future.

Table 1
Contest structure and rating system of the SDE 21/22.

				SDE21/22 Challenges		evaluation type	
	contests	**points**	**share**	**Design Challenge**	**Building Challenge**	**juried**	**monitored**
1	Architecture	120	12 %	•	•	•	
2	Engineering & Construction	120	12 %	•	•	•	
3	Energy Performance	120	12 %		•		•
4	Comfort	100	10 %		•		•
5	House Functioning	80	8 %		•		•
6	Sustainability	100	10 %	•	•	•	
7	Affordability & Viability	100	10 %	•	•	•	
8	Urban Mobility	80	8 %	•	•	•	
9	Innovation	100	10 %	•	•	•	
10	Communication, Education & Social Awareness	80	8 %	•	•	•	
		1000	100 %				

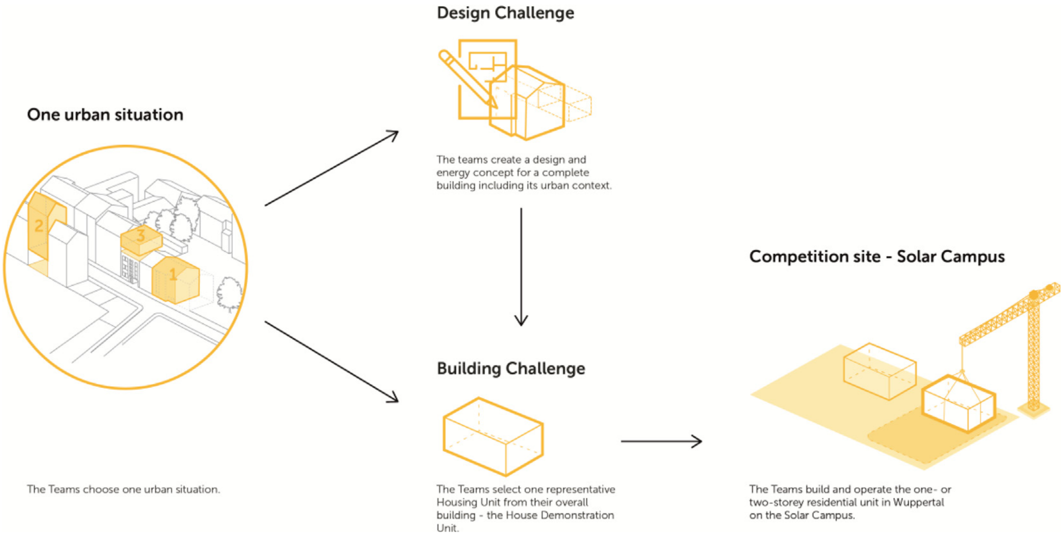

Fig. 1. The new course of the competition. The "design challenge" addresses real urban situations. The demonstration units for the "building challenge" on the common site form representative parts of the design challenge project.


a) b)

Fig. 2. The overall winner, Team "RoofKIT". Illustration of the design challenge contribution with a vertical extension of an existing building in Wuppertal (a) and photo the representative demonstration unit on the competition site (b). Illustration: Team RoofKIT, Karlsruhe Institute of Technology, Photo: SDE 21/22.

3. Buildings, energy concepts and building energy systems

The following chapter briefly describes the main properties of the buildings in the competition with respect to energy design and engineering. The "SDE 21/22 exhibition booklet" and the "SDE 21/22 competition source book" are publicly available on the competition website and illustrate the projects in detail [16]. Links are provided to the individual team websites.

The primary construction of the HDUs was a timber frame or a solid timber construction. The background to this was the necessity to transport the buildings several times and to thereby limit the weight [20]. Furthermore, when adding a storey to an existing building, the static requirements also speak in favour of lightweight timber constructions. The only exception was the building by the team from Grenoble (GRE), which used load-bearing precast concrete elements based on the construction method of the existing building. In timber constructions, the thermal capacity, which is important for the heating system operation in the winter (refer to chapter 4.4) and the indoor climate of non-air-conditioned buildings in the summer, is created through the interior plaster on ceilings and walls as well as the floor structure. Clay plasters or clay building boards were used in eight projects.

The on-site buildings differ significantly in size (67 m^2 to 139 m^2, Ø 97 m^2) and roof type (Table 2). In three cases, subvolumes were only considered in terms of the indoor climate monitoring, as they were separate living areas in the buildings which were only partially air-conditioned (HFT, HSD, TUD). In two buildings, the air-conditioned spaces extended over two floors (FHA, UPH). Three buildings have non-air-conditioned conservatories (ION, ITU, UPH).

In many aspects, most of the demonstration buildings follow the basic design principles of passive houses [33]. The buildings were predominantly constructed on a compact basis, with form factors between 0.7 m^{-1} (FHA) and 1.4 m^{-1} (UPH), and U-values between 0.09 W/m^2K (ROS) and 0.22 W/m^2K (NCT) for the opaque components. Biotic insulation materials such as wood fibre, cellulose, cork, straw or cotton were predominantly used rather than mineral wool or polystyrene. The windows were dominated by coated 3-pane thermal insulation glazing. Exceptions were vacuum glazing (ROS), partly solar control glazing (ION), and 4-pane glazing (HBC). Walls without any windows were the typical feature in terms of the task of filling a gap between buildings (FHA, ITU, UPH, UPV) or in the case of one residential unit adjoining another (HBC). In the case of solar shading, movable, externally-mounted solar shading dominates, which is usually activated via the building automation system. Just two projects worked with window ventilation only, while all the others used energy efficient mechanical ventilations systems with heat recovery (7) or heat plus humidity recovery (7). Before the backdrop of the increasing importance of the heat demand for domestic hot water, in the case of small space heating demands, four teams used heat recovery systems for showers.

Starting from a heat supply with district heating, natural gas or oil in the existing buildings under investigation in the design challenge, the majority (9 of 16) of the teams' thermal energy concepts for the renovations and extensions were based solely on the use of electric heat pumps with waste heat, geothermal heat and solar energy or outside air as heat sources. Only five teams combined the heat pumps with gas boilers (UPC, HBC), district heating (ROS, ITU) or wood pellet heating (GRE). The HDUs on the Solar Campus were "purely electric houses", using electricity as the sole energy source for all energy services. In this respect, it was not always possible for the energy concepts in the design challenge to be transferred to the building challenge unchanged. The energy concept was evaluated by a jury on the basis of on-site visits and the documentation provided for the competition (Fig. 3). This includes the calculations and simulations for the design challenge, as well as the HDU during its design phase. Accordingly, the students learn to document the process and the findings from the planning with text, figures, summarised reports and presentations in a far more intensive way in comparison with conventional university seminars.

In terms of energy, the aim was to generate at least as much electricity on site as is needed to run the HDUs (net zero energy solar building, [2]). Before the backdrop of the moderate climatic conditions in June in Wuppertal (Fig. 6), the rules prohibit the active heating or cooling of the buildings including the running of the heat pumps, except for DHW. It was necessary for the indoor

Table 2
General characteristics of the 16 design challenge and building challenge projects in competition. The characteristics of the solar systems are listed and in Table 3 and 4, chapter 6. Half of the projects are participating in the post competition living lab, refer to chapter 8.

		design challenge		living lab	building challenge/ HDU							
team	city, country	Urban task	Task location		floor area [m^2]	# floors conditioned	conservatory	Construction type	Roof type	Service room	Mechanical ventilation	DHW heat recovery
CHA	Gothenburg, SE	extension	Gothenburg		67	1		elementary*	low-pitched roof	internal	windows	
CTU	Prague, CZ	extension	Prag	•	68	1		hybrid	flat	internal	central HR	
FHA	Aachen, DE	urban gap	Wuppertal	•	156	2		modular	flat	external	central HR	•
GRE	Grenoble, F	extension	Chateau-Bernard		64	1		hybrid	flat	external	central ER	
HBC	Biberach, DE	extension	Wuppertal	•	60	1		elementary	flat	external	central ER	
HFT	Stuttgart, DE	extension	Stuttgart		95	1		elementary	flat	internal	windows	•
HSD	Düsseldorf, DE	extension	Wuppertal	•	115	2		modular	flat**	external	central HR	
ION	Bucharest, RO	extension	Wuppertal		93	1	•	hybrid	flat	external	central HR	
ITU	Istanbul, TR Lübeck, DE	urban gap	Kiel		125	1	•	elementary	mixed	internal	central HR	
KIT	Karlsruhe, DE	extension	Wuppertal		55	1		modular	saw tooth	internal	decentral HR	
NCT	Taipeh, TW	urban gap	Taipeh	•	123	1		elementary	saddle	internal	central ER	
ROS	Rosenheim, DE	extension	Nuremberg		118	1		modular	mixed	internal	central ER	•
TUD	Delft, NL	extension	The Hague	•	102	2		modular	flat	external	central + decentral ER	•
TUE	Eindhoven, NL	extension	Wuppertal		67	1		hybrid	flat	internal	central ER	
UPH	Pecs, HU	urban gap	Pecs	•	139	2	•	hybrid	flat	external	central ER	
UPV	Valencia, ES	urban gap	Valencia	•	71	1		hybrid	flat	external	central HR	
			average floor area [m^2]:		97							

* partly 3D printed
** partly glazed roof sheds

HR heat recovery
ER enthalpy recovery

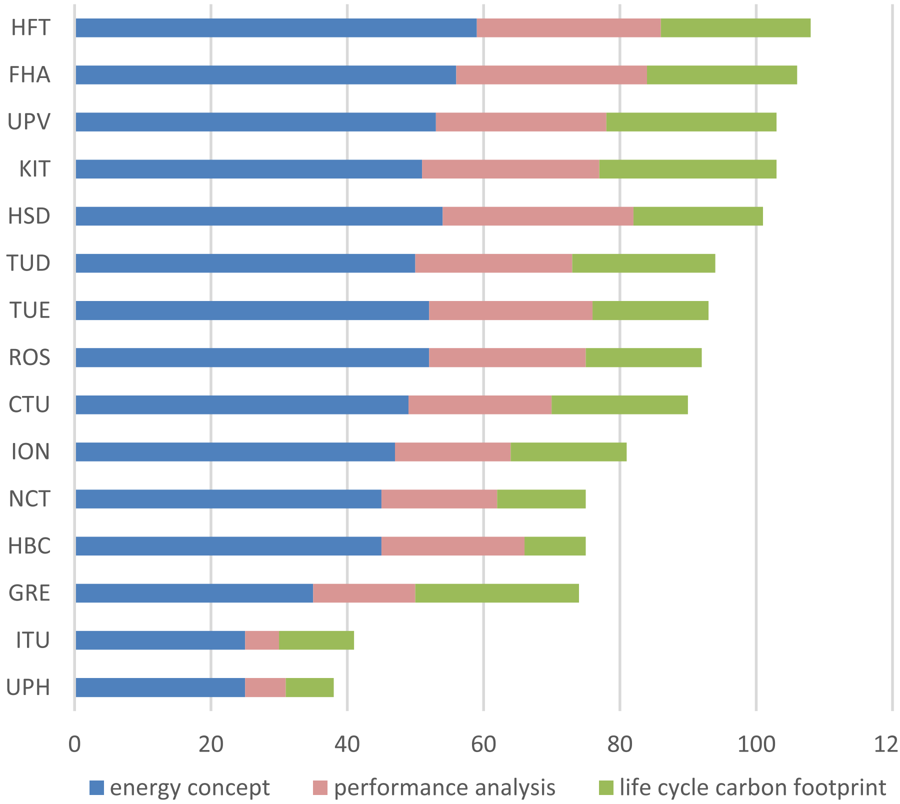

Fig. 3. Jury scoring of the buildings in the contest 2 “Engineering & Construction” with a focus on the buildings energy concepts in the design challenge. A maximum of 120 points were achievable. The abbreviations on the y-axis refer to the teams listed in Table 2.

comfort zone to be maintained by free-floating operation under the effects of the appropriate ventilation and shading [15].Fig. 7.

As regards the limits stated in the competition rules, the solar power systems were all of a similar size, with approx. 3 kW_p. The differences in the monitored energy balance are therefore the result of the system alignment, performance and energy consumption. At the intersection to the power grid, it became measurable as to which share of the generated electricity was used by the HDU itself and which was fed into the grid. With battery storage units of the same size (2.5 kWh) in all houses, this demonstrates the adaptation of the consumption in terms of the availability of the solar power (demand-side management). Battery charging from the mains was not permitted. The sizing of the heat pump was completed by the teams individually, with no capacity limitation set according to the rules.

4. Monitoring and testing

In the competition, the three disciplines “Energy Performance”, “Comfort” and ”House Functioning” were evaluated entirely from measurements and evaluation rules, Table 1 [5]. The rules defining the scoring procedure to transfer the measured data into points were made available to the teams in advance to allow them to create suitable building operation strategies and set priorities. With respect to the central topic of the paper, Fig. 4 illustrates the resulting scoring for the energy performance discipline of 15 demonstration buildings monitored. The maximum score of 120 points is attributed to 5 sub-contests:

- Energy consumption (30): All available points are earned by the house with the lowest energy consumption, with reduced points if the calculated house consumption is between the lowest consumption and 2.0 times the average consumption. Reduced points are scaled on a linear basis. No points are earned if the calculated consumption is equal to or higher than 2.0 times the average consumption.
- Energy balance (30): All available points are earned by the house with the highest energy balance, reduced points if the calculated house energy balance is between the highest energy balance and 0. Reduced points are scaled on a linear basis. No points are earned if the consumption exceeds the generation.
- Self-consumption (20): All available points are earned by the house with the highest self-consumption, reduced points if the calculated house self-consumption is between the highest self-consumption and 0. Reduced points are scaled on a linear basis. No points are earned if the calculated self-consumption is 0.
- PV system performance (20): All available points are earned by the house with the highest PV system performance ratio, reduced points if the calculated house PV system performance ratio is between the highest PV system performance ratio and 0. Reduced points are scaled on a linear basis.
- Grid interaction (20): All available points are earned by the house with the lowest energy costs, reduced points if the calculated costs are between the lowest and the highest. Reduced points are scaled on a linear basis.

4.1. Monitoring

The measurement system for the competition was based on a networked data logger in each house for the continuous recording of at least 16 data points per house. This included:

- 3 electric meters for electricity generation, consumption by sectors and grid interaction (Modbus RTU Smart Meter, Fig. 5. The variables not measured were calculated from the energy balance.

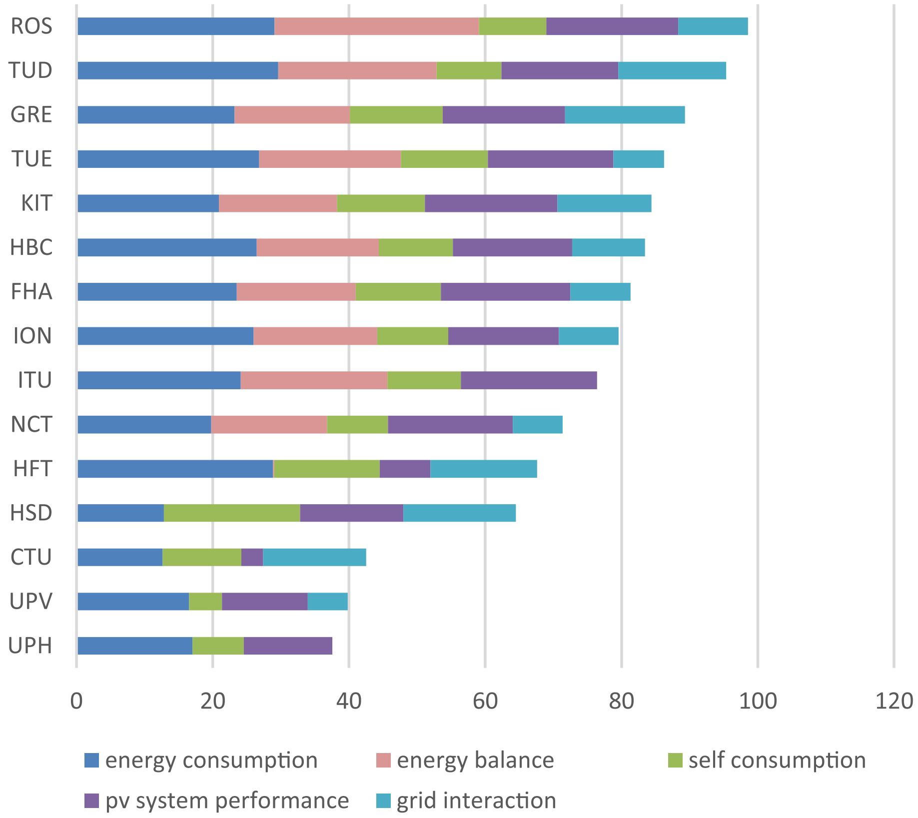

Fig. 4. Scoring of the buildings in the energy performance contest 3 based on monitored data for the demonstration unit. According to the rules, a maximum of 120 points were achievable in this contest. The abbreviations on the y-axis refer to the 15 teams in competition.

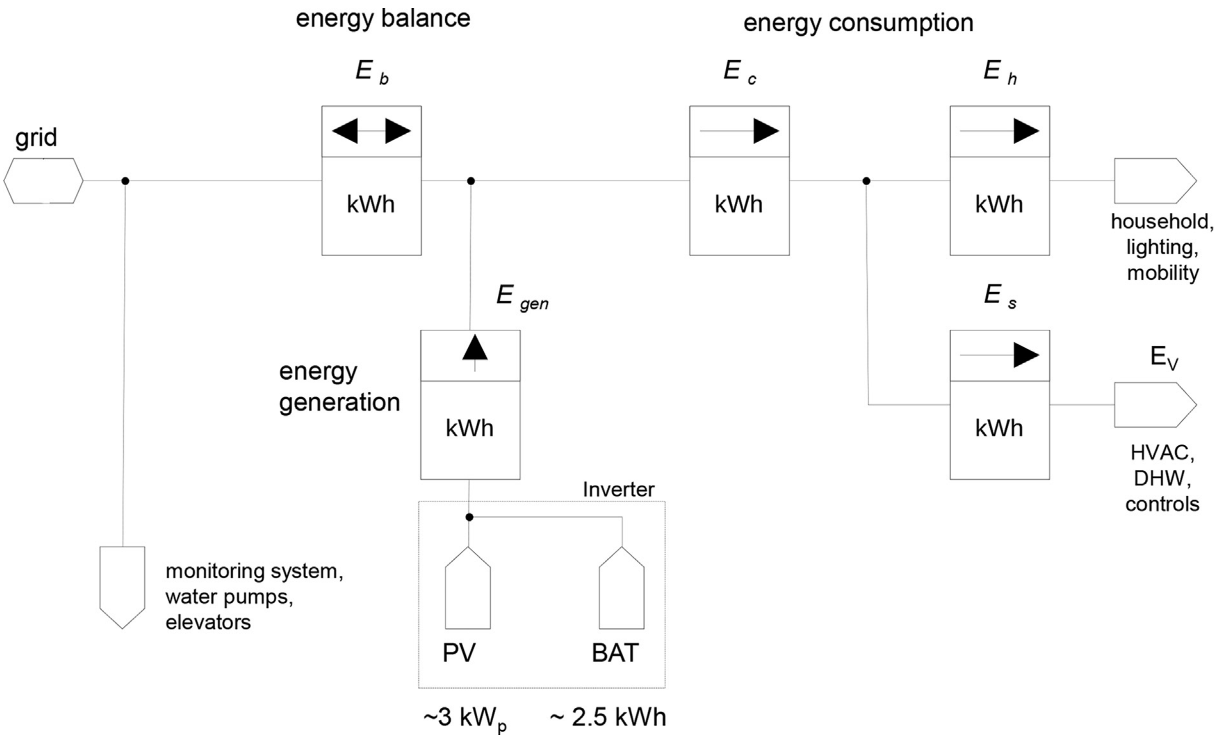

Fig. 5. The standard equipment was three digital electricity meters per house to determine five forms of energy consumption. The amount of energy generated by solar E_{gen} was measured on the AC side, also taking the battery storage into account.

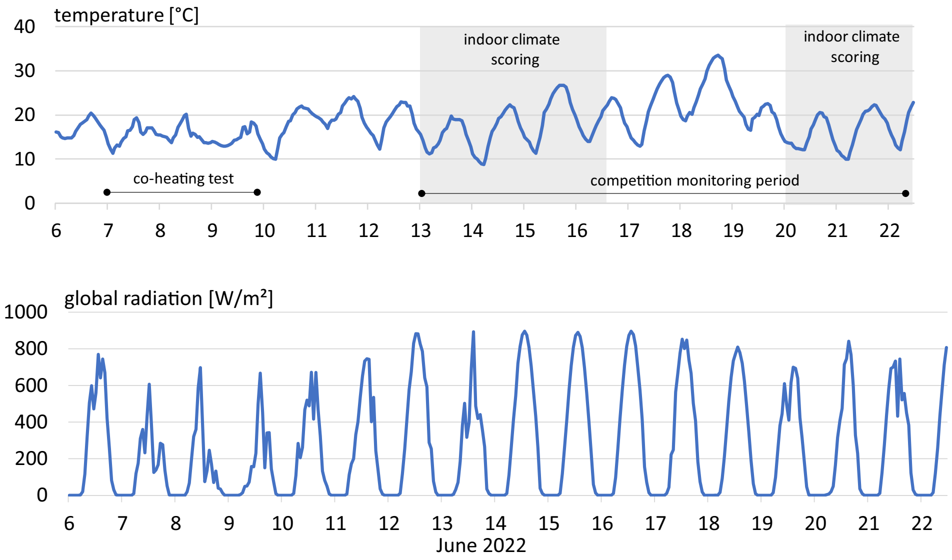

Fig. 6. Presentation of the main weather data during the competition based on hourly averages. The weather data was also monitored for the co-heating test prior to the competition (refer to chapter 4.4).

Fig. 7. A student from the TUE Team masking the joints of prefabricated façade elements for air tightness.

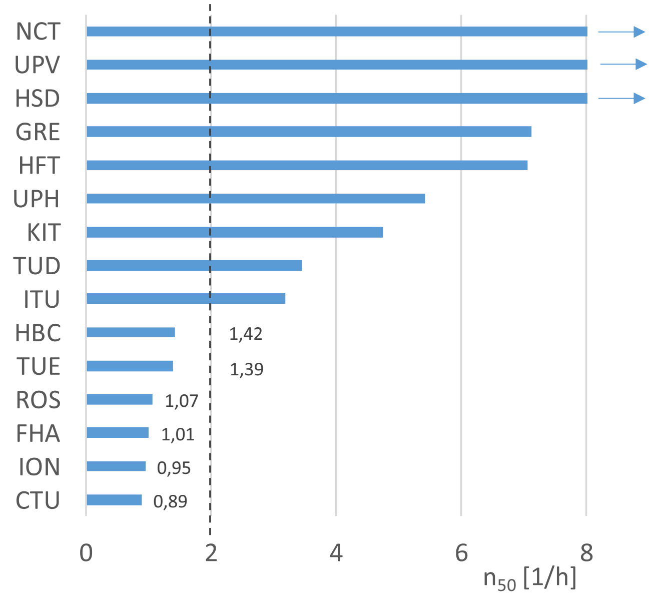

Fig. 8. Measured air exchange rates n_{50}. The dashed line at 2 marks the limit up to which points were awarded in the competition.

- 1 to 2 irradiation sensors for the PV system analysis (calibrated solar cells)
- Indoor climate sensors in the living room (air temperature, humidity, CO_2, illuminance) and bedroom (air temperature, humidity) with digital sensors via Modbus RTU in a height of 90 cm, Fig. 9
- Household appliance function with thermocouples (6 temperatures).

Data was collected every minute and aggregated into 15-minute totals or median data as basis for the evaluation. Indoor climate measurements were only taken into account on seven selected days when no visitors were allowed in the houses (Fig. 6); the energy and equipment measurements were taken continuously over ten days. The respective charging states of the energy storage units were recorded at the beginning and at the end of the competition by reading thermometers and charge level indicators. In total, over half a million pieces of data were collected during the competition. The monitoring system was also used before the actual competition days for the co-heating tests (chapter 4.4). Some of the buildings' properties were determined within the scope of special test measurements, such as the airtightness test (chapter 4.2). Students had real time access to a data dashboard on the web to discover the performance of their own house but were not able to see the performance of the other houses. This was to prevent them from focusing on their performance in comparison with the other teams.

4.2. Climate

Winters and summers with moderate temperatures are typical of the weather in Wuppertal. The long-term annual average temperature is 10.5 °C, the total global radiation is 942 kWh/m^{2}a. With respect to such factors, the energy planning for residential buildings typically focuses on providing thermal protection in the

Fig. 9. Example of a room with a fan heater (blue) and a tripod (yellow) with indoor climate measurement equipment in the TU Delft building (TUD).

winter. During the competition, the weather data was monitored and the students had live access to the data to optimise the building operations (Fig. 6). This was particularly important so as to be able to operate the ventilation and shading properly and to optimise the energy management with respect to self-consumption and grid interaction. The students learned how the weather data and information are useful so as to fulfil the comfort requirements and reduce the carbon emissions. The students incorporated the weather data in their houses' building automation system and simulation tools (Fig. 12).

4.3. Air tightness testing

One of the subcategories in the "Comfort" contest seven concerns the air tightness of the building envelope. The test was performed after closing all the closable openings and sealing all the existing systems and equipment for ventilation. The focus of the learning was therefore on the building envelope. In this case, the term "building envelope" means the envelope of the heated building volume or partial volume, which was also defined for the co-heating tests and the indoor climate measurements. The air exchange rate was measured at a test pressure difference of 50 Pascal according to EN 13829 [21]. The team with the lowest air exchange rate achieved the full score of 10 points. No points were awarded for an air exchange rate above 2 h^{-1}, and the intermediate results were interpolated on a linear basis. The measured infiltration rates were between 0.89 h^{-1} (CTU) and 27.15 h^{-1} (NCT). Six buildings achieved remarkably good results, while nine demonstration buildings were measured with values above 2 h^{-1} and were therefore awarded no points (Fig. 8).

The leakage detection during the measurement of the buildings led to a basic differentiation between leakages due to the construction and leakages due to the building concept. All the results have to be considered before the backdrop of the small size of the buildings and the short construction phase (14 days) which, for the most part, was not carried out by skilled workers. It is particularly noteworthy that the majority of the buildings with good air tightness values were built entirely by students. Apart from the educational value of the test, on the basis of the leakage detection, it is possible for some findings to be transferred to building practice:

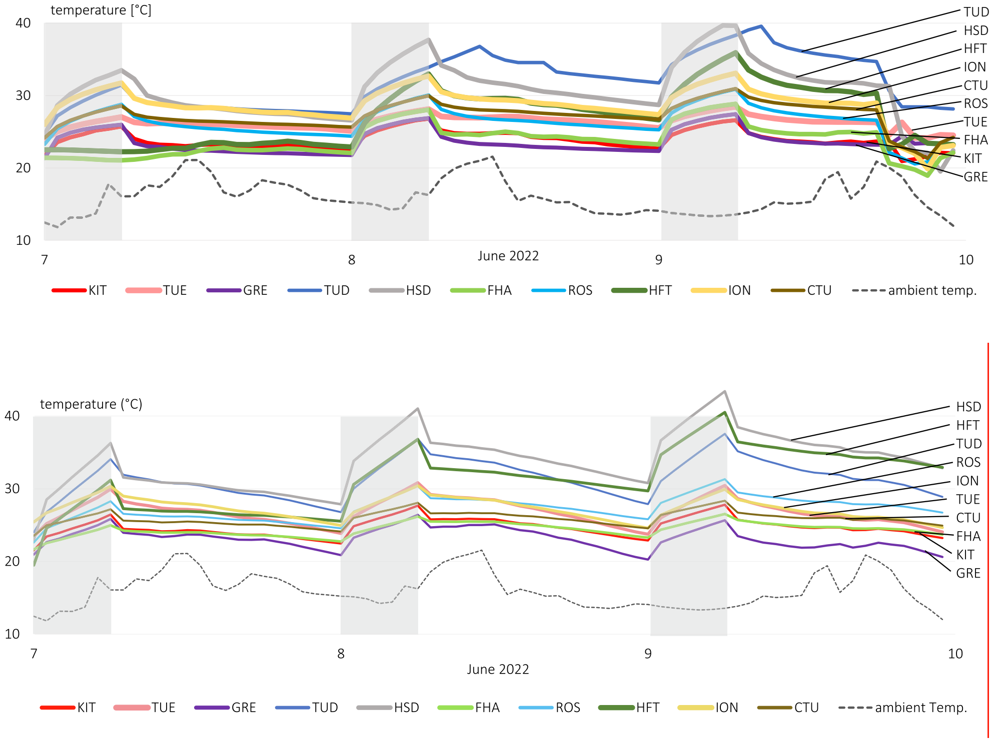

Fig. 10. Comparison of the measured (upper diagram) and simulated (lower diagram) hourly mean temperature data for the main living space of 10 buildings compared with the outdoor air temperature. The times with a grey background indicate the operation of the fan heaters.

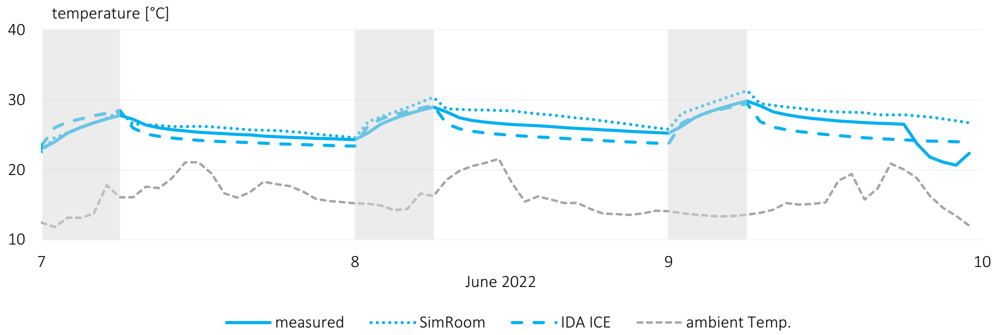

Fig. 11. Example of a model comparison for the demonstration unit of the Rosenheim team (ROS).

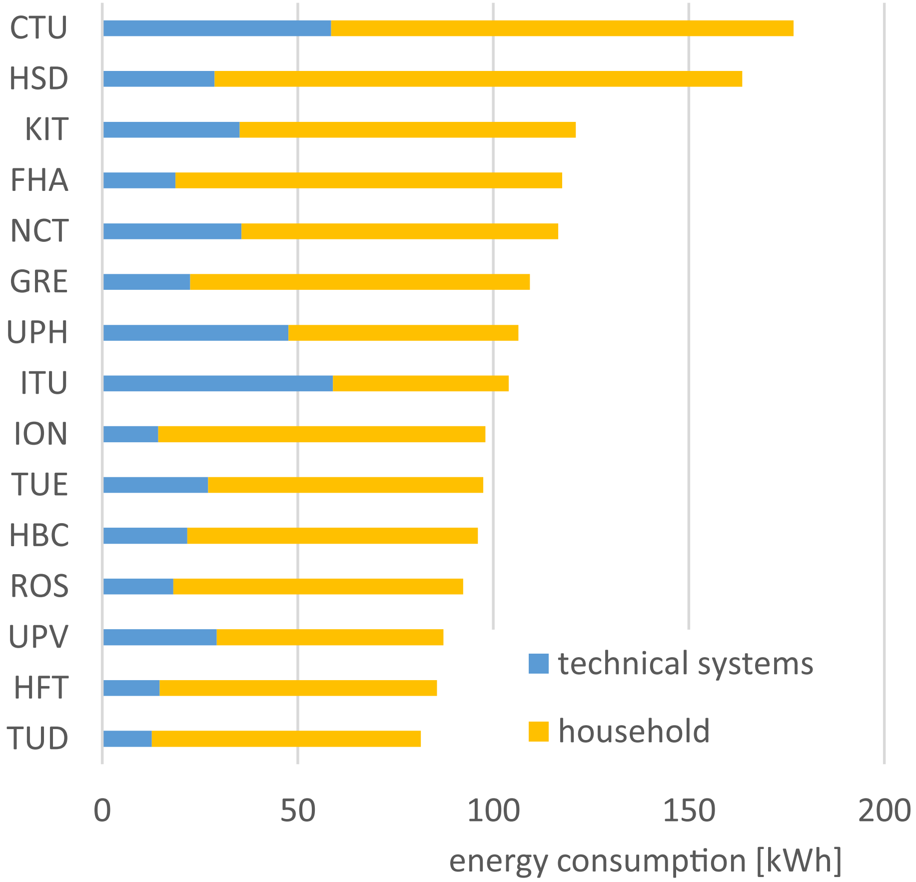

Fig. 12. Composition of the houses' electricity consumption for the household (incl. lighting) and technical systems throughout the competition period of 9 days.

- Leaks relating to windows, doors and system components are comparatively easy to detect and can be quickly rectified. The contact pressure and joint tightness must be checked.
- Building concepts with a separable and adhesive-free construction and connection design (KIT, HSD) need to be further developed in terms of the requirement of an airtight building envelope.
- Locating the mechanical rooms within the heated envelope results in significantly lower air infiltration rates.

Announcing and running infiltration tests for the first time in an SDE raised the awareness of the students for the importance of the sufficient detailing of the planning and high level of precision during the work on the construction site.

4.4. Dynamic Co-Heating testing

Considering the fact that buildings in Central Europe consume the greatest amount of energy in the winter, holding a building energy competition in June or September does not initially seem didactically relevant. Bearing this in mind, additional heating tests were designed and carried out which were referred to as "co-heating tests" [22]. These involved thermal stimulations by temporarily carrying out the supplementary heating of the empty buildings or rooms to a temperature level significantly above the ambient temperature. The tests took place on three consecutive days between the end of the assembly phase and the beginning of the competition. Immediately afterwards, the students were asked to carry out their own thermal simulations with measured weather data and to compare the indoor climate with the measurement results (sub contest: Performance Gap). For this purpose, the educational software "SimRoom" was provided to each team with predefined settings and the current on-site weather data [23].

For the experiment, fan heaters with a 3 kW power rating were used simultaneously in the ten buildings that were ready in time (Fig. 9). The other buildings were unable to participate because the construction work was ongoing. The investigation was performed in terms of the area within the buildings intended for full heating. These were partially smaller partial volumes of the demonstration units (TUD, HSD, HFT). Via a switching signal from the data loggers, the heating was activated at a full and constant output between midnight and 6 am. No people were present in the houses, but the usual household appliances were connected (waste heat from refrigerators, etc.). The ventilation systems had been deactivated and all openings were closed as a result of the air tightness measurements that took place just before. Where present, movable sun protection devices were closed to pretty much exclude the effect of solar gains. Due to delays in the construction process, it was not possible to start with a uniform temperature in the buildings, contrary to the planning.

For comparability with the results of the simulation, the measured values were combined into hourly averages. Due to construction delays, two teams started on the second day of the test sequence (HFT, FHA). For the team from Delft (TUD), due to heat-related problems with the data logger, the fan heater was in operation for longer than planned on the second and third days. The end of the series of tests was marked by strongly scattered measurement curves (window opening, occupancy ...). The reaction to the operation of the fan heaters can be clearly seen in the measurements. Their deactivation leads to a decreasing room temperature until the next heating operation. The decay behaviour reflects the thermal insulation level, the air tightness and the heat capacity. In the trend over the three days, the temperature level increases in the buildings and reaches peak values of 40 °C (HSD, TUD).

At first glance, the SimRoom simulation results from the teams describe the thermal behaviour of the buildings quite well, with the exception of the errors in the realisation of the test, Fig. 10. The faster temperature increases in HFT and HSD houses were caused by the comparatively small room volumes. No parameter adjustments were made in the tool for the comparison. The results of the air tightness measurements were not yet known to the teams at this point. Therefore, this already explains some of the differences. The monitoring data is a potential source of further simulation studies for academic education, namely the parameter identification procedures, and is freely downloadable on the competition knowledge platform [5]. An initial application is indicated by Fig. 11: the team from Rosenheim (ROS) has incorporated the monitored weather data into its detailed simulation model from the planning phase based on the IDA ICE software for the purposes of comparison and further studies. The SD is a valuable source for teaching on the critical use of simulation tools to stimulate the early design phase [24]. This is particularly true in the case of qualified monitoring results for comparison purposes.

5. Energy performance

5.1. Energy efficiency

In terms of energy use, the consumption by household appliances, lighting and small consumers was dominant over building services, as expected by the students from their calculations during the planning phase. There is a factor of 2.2 between the most energy efficient project (TUD) and the project with the highest consumption (CTU, Fig. 12). In addition to the differences in the consumption by household appliances, there were differences due to the types and methods of laundry drying (tumble dryer, washing line or both), the presentation media (screen or projector) and the lesser or greater intensity of the used lighting, for example. Despite the existence of energy-efficient systems, the lowest consumption was only achieved by an active form of demand-side management to reduce the operation of devices as far as possible. At 367 W, the average power was slightly above the monitoring results from the 2014 edition of the SDE (314 W, [12]). Extrapolated to one year, this results in a household electricity consumption of 3,211 kWh or 33 kWh/m^2. This value is 65 % higher than the electricity demand typically accounted for during the planning of net energy positive residential buildings in Germany (20 kWh/m^{2}a [25]). The reason for this is due, on the one hand, to the comparatively small buildings that are fully equipped with all the necessary equipment and, on the other hand, to the competition rules. The "house functioning contest" is obviously not a representative depiction of conditions in the typical German household.

The building services' energy consumption primarily involved ventilation, the heating of water and building automation, because the active space heating and cooling using the heat pumps was excluded. The differences between the projects are even greater, with a factor of 4.6. Among others, this is affected by whether solar thermal systems are responsible for the preparation of hot water or heat pumps or cartridge heaters are used. At 135 W, the average power was identical to the monitoring results from the 2014 SDE [12]. This is surprising at first glance, as active space heating and cooling was permitted by the rules in that year, theoretically increasing the HVAC load. On the other hand, however, the weather conditions during the typical competition periods in spring or autumn in Europe are usually moderate. An extrapolation to the annual data and a comparison with building practice is not possible, as the heating and cooling were not active during the event.

5.2. Energy balance

All of the buildings apart from two (CTU, HSD) show a clearly positive or even energy balance when comparing the generation and consumption values (Fig. 13). The high energy consumption in combination with the less than ideal operation of the solar power systems were the decisive factors for the negative balances. This is also illustrated in the energy balance development during the competition days (Fig. 14). It remains the task of the teams to find out what the reasons are. The solar yield of all systems in normal operation during the competition days ranges between 43 kWh/kW$_p$ (HSD) to 60 kWh/kW$_p$ (ROS). This reflects the orientation and inclination as well as the performance ratio (refer to chapter 6.2).

In contrast to the generation/consumption balance, the import/-export balance at the interface to the power grid reflects the self-consumption of the solar yield for the building use (sub contest 3.3, Fig. 4). Self-consumption includes the instantaneous consumption of solar power as well battery-buffered consumption relating

Fig. 13. Comparison of power generation and consumption as well as export and import at the interface to the power grid as total values throughout the competition period. Each pair of dots indicates a building.

to the generation, refer to Fig. 5. The average self-consumption index I_{SC} based on 1-minute resolution data was found to be 49 % with (logically) the highest value of 84 % for the buildings with the highest consumption (HSD, Fig. 15). By contrast, the index of self-sufficiency I_{SS} characterises the proportion of electricity consumption that is covered directly by the solar and storage system. This is expressed as a percentage of the consumption E_C. The maximum self-sufficiency was achieved by the TUE team with 87 %, the average of all projects was found to total 65 %. Due to the battery systems, the self-consumption rate and degree of self-sufficiency are significantly higher than those in systems with complete surplus feed-in. This is especially true in the light of the high solar radiation values during the competition period, as shown in Fig. 6 (Ø 292 W/m^2). Both indices cannot be scaled up to annual data due the strong seasonal variation of the yield and consumption.

$$I_{SC} = \frac{E_{gen} - E_{feed-in}}{E_{gen}} \tag{1}$$

$$I_{SS} = \frac{E_{gen}}{E_c} \tag{2}$$

5.3. Energy flexibility

The new challenge in sub-contest 3.5, “grid interaction”, was the automatic adjustment of the import and export of electricity

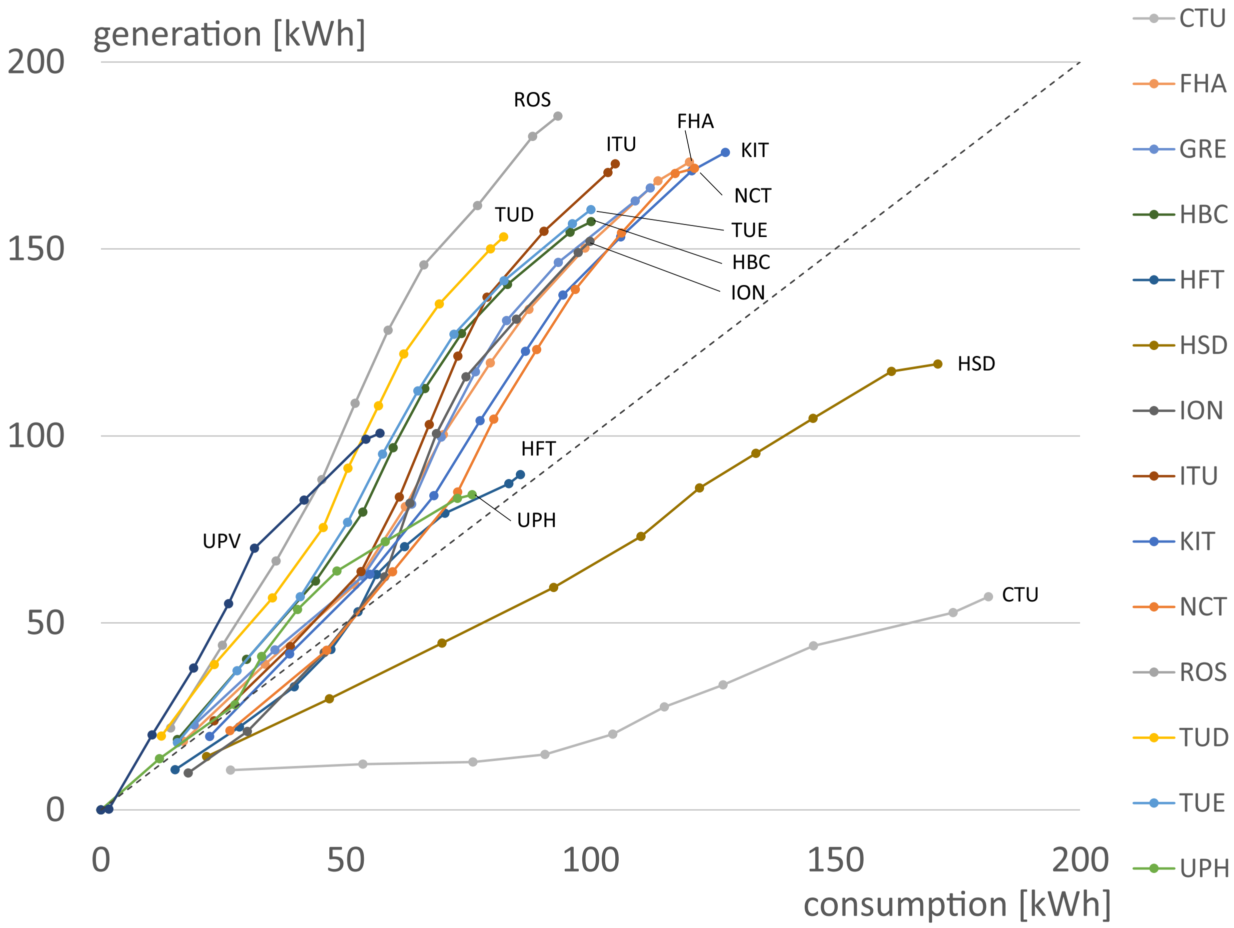

Fig. 14. Development of power generation and consumption over the 10 days of the energy competition. Each line indicates one of the 15 buildings, each dot a day. Some of the teams were unable to participate in the competition on all days due to technical problems.

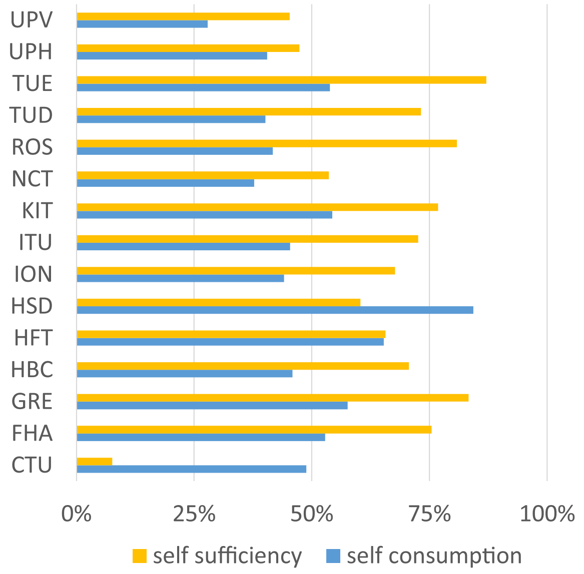

Fig. 15. Comparison of the indicators for self-sufficiency I_{SS} and self-consumption I_{SC} based on the monitoring data with 1-minute resolution.

in terms of the short-term incoming price signals from the power grid. This contest makes students aware of the need for flexible building energy use within the framework of power grids that have a high rate of fluctuation due to power generation using renewables such as wind and solar [26]. One day in advance of the two subsequent days (20th and 21st June), all of the teams received time-variable electricity rates with 15-minute rate details (Fig. 16). There were periods with free electricity as well as periods with very high feed-in rates. The flexible rates are in concurrence with the constant standard rates of 10 €ct/kWh for feed-in and 30 €ct/kWh for revenue. The highest score was achieved by the team with the most economical operation compared with operation at constant rates on the relevant two days (Fig. 4). A building automation system was required to take the variable tariffs into account, for the battery management, for example. If all 15 buildings are considered together at the level of the campus grid, the behaviour is clearly visible by the 20 kW load peak in the afternoon on 21st June, when the electricity provided was free of charge (Fig. 17). On all the other days, the load peaks are usually around 10 kW and in the early morning. This shows that the 2.5 kWh batteries are typically too small to cover the early morning power consumption in full. Otherwise, the feed-in power load peaks exceed those of the electricity consumption. The theoretical feed-in peak would be roughly 45 kW (15 x 3 kW) as long as no battery power is fed in.

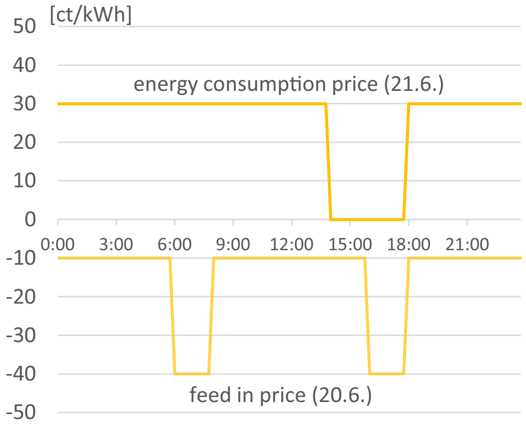

Fig. 16. Flexible rate information given to the teams for 20th June (preferred feed-in) and 21st June (consumption adjustment). Positive: revenue, negative: costs.

6. Solar system integration

The architectural and technical integration of solar systems in existing buildings and their extensions are key tasks in a strategy towards achieving climate neutrality through the decarbonisation of the building energy supply [34,35]. Various international working groups within the scope of the solar heating and cooling programme of the IEA have previously addressed this topic intensively with comprehensive reports from different perspective [27]. A cross-sectional study reviews the application of building-integrated photovoltaics (BIPV) within the scope of the Solar Decathlon Europe [11]. The student teams investigated the use of solar thermal, solar power and hybrid systems in the context of their individual projects, starting from the early drafts of the design challenge for the sizing and detailing of the systems, to the realisation phase and the operation of the demonstration unit. The SDE 21/22 included an impressive range of solutions with a high degree of sophistication from the technical and design perspectives.

The type of solar system integration in the demonstration unit reflects the scale of the design challenge, as the demonstration unit should be a representative part of it (Figs. 1 and 2). As a result of this, combined solutions on roofs and façades were often applied, which, when taken alone, are not necessary for operating the demonstration buildings, the entirety of which were not therefore actively connected in terms of the electricity or the thermal energy during the competition.

6.1. Architectural integration

Solar systems are a key element in the SDE houses. They may be intentionally visibly highlighted or inconspicuously integrated into the architecture. As summarised in Table 4, both strategies were presented on the solar campus. The shape of the roof is crucial for the architecture, the visibility and the integration of the solar systems. The majority of teams chose a flat roof, as shown in Table 2. Flat roofs allow the modules to be aligned in the ideal way in terms of their orientation and inclination, regardless of the orientation of the building itself. These systems were practically invisible for the visitors to the competition site, especially in the case of the two-storey constructions. Due to the non-visible application, standardised, highly efficient solar systems can be used, thereby avoiding the costs of project specific constructions (Fig. 2, Fig. 18, Fig. 19). For economic reasons in particular, this is common practice in large building projects in Europe. Solar systems on flat roofs can also provide shade for rooftop patios and conservatories when they are part of common spaces in urban apartment buildings. The daylight shining through and the view from beneath the respective modules provided a wide variety of variants. The HBC team used innovative, tubular thin film photovoltaics (η=5.5 %) as pergola roofing. These were originally developed for large-scale use in agriculture (Agri-PV, Fig. 20). Apart from many parts of the timber construction, the GRE team reapplied the glass-glass modules from their SDE 2014 house (Fig. 21).

The façade integration of solar systems typically needs more attention for the adjustment of the sizes, colours and construction details. A typical arrangement is a ventilated curtain wall. The solar system assumes all the tasks of an external cladding. Some teams used coloured solar cells (FHA, ROS, Fig. 22 a) or modules with coloured ceramic printing at the top (TUD, TUE, Fig. 18, Fig. 22b)

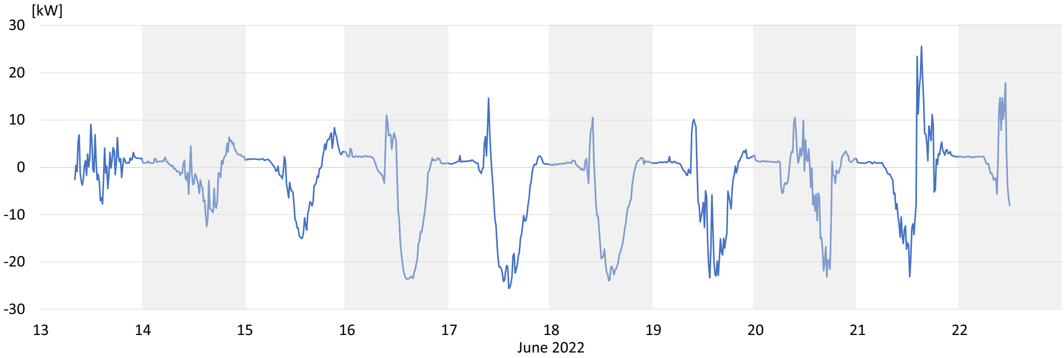

Fig. 17. Development of electricity load (positive) and feed-in (negative) at the level of the Solar Campus power grid with all 15 buildings connected.

Fig. 18. Roof mounted, non-visible standard PV modules together with blue ceramic image print PV on the south façade of the TUD house © Sigurd Steinprinz, University of Wuppertal.

Fig. 19. Non-visible thin film PV on the saw-type metal roofing of the CTU house © Sigurd Steinprinz, University of Wuppertal.

Fig. 20. Black, vertical PVT collectors on the east façade, and horizontal thin film PV tubes covering the roof garden of the HBC building © Sigurd Steinprinz, University of Wuppertal.

Fig. 21. Daylighting PV modules (front) and PVT collectors (back) cover the roof terrace of the GRE house © Sigurd Steinprinz, University of Wuppertal.

in ventilated curtain wall constructions. Typical module efficiencies are 12 % compared to current practice, with 20 % for black, high efficiency modules. The HFT team experimented with a shading curtain consisting of a metallic grid with integrated, rhomb shape polycarbonate plates with organic solar cells (η_{PV} = 2–4 %, Fig. 22 d, [28]). The roof-mounted PVT collectors on the KIT building have cupper coloured modules to visually comply with the cupper roof cladding (η_{PV} = 18 %, Fig. 2). Another approach was the integration of monocrystalline solar cells into multi-layer roof or façade thermal insulation glazing as is common in non-residential building projects (HSD, Fig. 22 c).

6.2. Technical integration

The majority of the teams installed their solar energy systems on site. In some cases, the systems were also installed in advance as part of the building envelope, transported as a whole and only complemented on site (KIT, TUE). When designing the PV power systems, all the teams pretty much reached the upper system scale limits according to the regulations (3 kW_p PV capacity, 2.5 kWh battery storage), and parts of the systems remained unconnected.

a b c d

Fig. 22. A) back-ventilated curtain wall façades with grey coloured pv modules at the ros building b) pv modules with a brown structured ceramic print on the curtain type façade of the tue building c) solar cell integration with variable density into moveable triple glazing in the façade of the hsd building. d) small rhomb shape organic pv modules integrated in a metallic grid on the roof and the façade of the hft building © Sigurd Steinprinz, University of Wuppertal.

In relation to the average net floor area of about 100 m^2 (Table 2), the specific power at about 30 W/m^2 is less than half of the power installed in the last two SDE editions (Table 5) [12]. The strict limitation by the SDE 21/22 rules therefore reflects the fact that the limited number of solar-exposed surfaces available in apartment buildings, and encourages energy efficiency measures for the achievement of a positive energy balance.

Monocrystalline silicon cells were used in the majority of the systems (Table 3). Their high efficiency enables a high yield with a limited surface area. Six teams used modules with a bifacial design to slightly increase the yield by using parts of the backside irradiation. Their effect varies with the mounting of the modules. The organic solar cells in the PV curtain of the HFT house demonstrate an experimental application of a new technology, (Fig. 22 d), covering large surfaces due to the low efficiency. Almost all teams had the batteries connected on the DC side, only the teams HSD and TUE used AC-coupling. Two teams used module-integrated inverters (TUE, GRE), as shown in Fig. 23. The yield of the solar systems in relation to the energy consumption of the houses is considered in the energy balance (chapter 5.2). By measuring the irradiation on the individual solar generators, it was possible for the quality of the system integration to be determined. This was included at a Solar Decathlon for the first time as a didactic incentive to critically investigate the quality of the overall system design.

For this purpose, the generated AC electricity yield E_{Gen} after the battery and the inverter (Fig. 5) was considered in relation to the theoretically-possible yield based on the PV output under standard test conditions according to the module certification (η_{STC}), the module area A_{PV} and the irradiation I_{PV} (performance ratio I_{PR}, [29]):

$$I_{PR} = \frac{E_{gen}}{I_{PV} \times A_{PV} \times \eta_{STC}} \tag{3}$$

The high values of 80 % (GRE) to 89 % (ITU) for half of the PV systems underline the quality of the technical implementation and the operation, Fig. 25 [30]. By comparison, the south east / south west oriented PV system on the campus of the University of Wuppertal achieved a value of 83 % in the same period without battery storage and the associated losses. Strategies to increase the performance ratio with fewer inverter losses were investigated by the HBC team with the use of DC electricity in the household, such as DC lighting and the DC charging of small equipment.

In total, 10 out of 16 teams used solar thermal systems (Table 4). In addition to the usual types of solar thermal collectors, five teams used hybrid collectors, also known as PVT collectors [31,36]. Again, the background to this is the shortage of solar exposed envelope space in apartment buildings. PVT collectors were used in the form of PV modules with integrated, rear piping (KIT, ROS, GRE) or collectors with plastic pipe systems that were clipped onto the back of standard PV modules for simple thermal activation (FHA). The HBC team used PVT collectors as curtain walls in the east and south façade with additional ambient air heat exchangers on their backs to significantly improve the thermal system behaviour in the direction of a year-round monovalent heating and DHW system in combination with a heat pump. The heat exchanger behind the 2.25 m^2 PVT module offers an active surface of 19 m^2 (Fig. 24) [32]. This means an increase of a factor of 8.4 compared with the standard PVT collectors that only benefit from the collector surface for the ambient heat collection. During the competition, most of the PVT collectors were operated in combination with heat pumps for the preparation of the hot water in combination with thermal storage tanks. As in all the previous competitions, the thermal yields of the collectors were not measured. In this context, a more detailed analysis is not possible and remains a task for the individual past competition research of the teams or as part of the living lab for past competitions (chapter 8).

In addition to the 10 official SDE disciplines, a special solar system award was offered by jury from the Solar Heating & Cooling Programme of the International Energy Agency (IEA) together with ISES, the International Solar Energy Society, to show appreciation for particularly outstanding energy concepts involving the interaction between photovoltaics and solar thermal energy. The two award winners were the TUE and FHA teams (Fig. 26).

7. Discussion

At a time where there is considerable uncertainty about our future supply of energy in Central Europe, the event and the university teams provided food for thought about how we can build our way out of the current crises surrounding energy and

Table 3
Type, properties and sizes of the solar systems in the house demonstration units.

				system sizes				PV type					ST type		PVT type		
ID	City	solar system	modul design	number of modules/collectors	Σmodule/collector area [m^2]	nominal elec. power [kW$_p$]	systems active in competion	bifacial	mono crystalline	poly crystalline	thin film	organic PV	tube collector	flat plate collector	plug & play	clip-on thermal activation	backside air heat exchanger
CHA	Gothenburg, SE	PV	glass/ laminate modules	*no details available*					•								
CTU	Prague, CZ	PV	PV laminated on metal panels	32	30.7	2.7	•				•						
FHA	Aachen, DE	PVT	glass/ laminate modules	16	14.8	3.0	•		•	•						•	
		PV	glass/glass modules	13	–	–	○		•								
GRE	Grenoble, F	PVT	glass/ laminate modules	4	7.5	1.6	•			•					•		
		PV	glass/glass modules	4	11.2	1.4	•			•							
HBC	Biberach, DE	PV	glass tubes	94	56.7	3.0	•				•						
		PVT	flat plate collector	22	49.5	9.9	*		•								•
HFT	Stuttgart, DE	PV	glass/ laminate modules	4	6.2	1.0	•			•							
		PV	rhomb polycarbonat sheets	224	41.7	0.9	•	•				•					
		PV	rhomb polycarbonat sheets	385	54.4	1.1	•	•				•					
HSD	Düsseldorf, DE	PV	insulation glass modules	–	–	2.7	•	•	•								
		PV	insulation glass modules	–	–	–	○	•	•								
ION	Bucharest, RO	PV	glass/glass modules	8	14.6	3.0	•	•	•								
		ST	vacuum tube	2	4.7	–	•						•				
ITU	Istanbul/ Lübeck, TR/ DE	PV	glass/glass modules	16	19.5	3.0	•	•	•								
KIT	Karlsruhe, DE	PVT	glass/ laminate modules	10	16.7	3.0	•		•						•		
		PVT	glass/ laminate modules	8	13.3	2.4	○		•						•		
NCT	Taipei, TW	PV	glass/ laminate modules	9	15.0	3.0	•		•								
		ST	vacuum tube	2	8.4	–	○						•				

(*continued on next page*)

Table 3 (*continued*)

				system sizes				PV type					ST type		PVT type		
ID	City	solar system	modul design	number of modules/collectors	Σmodule/collector area [m^2]	nominal elec. power [kW$_p$]	systems active in competion	bifacial	mono crystalline	poly crystalline	thin film	organic PV	tube collector	flat plate collector	plug & play	clip-on thermal activation	backside air heat exchanger
ROS	Rosenheim, DE	PVT	flat plate collector	8	15.0	3.0	●		●						●		
		PV	glass/glass modules	10	–	–	○	●	●								
		PV	glass/glass modules	15	–	–	○		●								
TUD	Delft, NL	PV	glass/ laminate modules	8	14.6	2.9	●		●								
		PV	glass/glass modules	36	–	–	○		●								
TUE	Eindhoven, NL	PV	glass/ laminate modules	5	8.6	1.8	●		●								
		PV	glass/glass modules	12	10.1	1.2	●		●							●	
		ST	flat plate collector	1	1.6	–	○							●			
UPH	Pecs, HU	PV	insulation glass modules	10	16.6	2.8	●	●	●								
UPV	Valencia, ES	PV	glass/ laminate modules	4	7.8	1.5	●		●								
		PV	glass/glass modules	9	12.6	1.5	●		●								
		ST	vacuum tube	3	7.1	–	○						●				
				average nominal power [kWp]		2.9											

PV: photovoltaik; PVT: hybrid collector; ST: solar themal collector; ○: system not in operation during the competition; *: only thermal part active in competition.

Table 4
Type of architectural integration of the solar systems in the house demonstration units.

		roof systems			facade systems					visual integration				
City	**Solar System**	**Roof integrated**	**Roof added**	**Pergola**	**East**	**West**	**South**	**South, tilted**	**west, tilted**	**Non-visible**	**Visible, added**	**Visible, integrated**	**coloured**	**Additional functions**
Gothenburg, SE	PV		•							•				
Prague, CZ	PV			•							•			shading
Aachen, DE	PVT		•							•				
	PV						○					•	•	curtain wall
Grenoble, F	PVT			•								•		shading
	PV			•								•		shading, daylighting
Biberach, DE	PV tube			•							•			shading
	PVT				•		•					•		curtain wall
Stuttgart, DE	PV		•							•				
	PV		•								•			shading
	PV				•	•	•				•	•		shading
Düsseldorf, DE	PV	•										•		insulation, shading, daylighting
	PV				○	○	○					•		insulation, shading, daylighting
Bucharest, RO	PV		•							•				
	ST tube		•							•				
Istanbul/ Lübeck, TR/DE	PV								•			•		shading, daylighting
Karlsruhe, DE	PVT		•							•			•	
Taipei, TW	PV		•								•			
	ST tube		•								•			
Rosenheim, DE	PVT		•								•			
	PV			•	•							•		shading, daylighting
	PV						○					•	•	curtain wall
Delft, NL	PV		•							•				
	PV						○					•	•	image print, curtain wall
Eindhoven, NL	PV		•				•					•		
	PV					○	○					•	•	curtain wall
	ST flat	•					•					•		
Pecs, HU	PV							•				•		shading, daylighting
Valencia, ES	PV		•				•				•			
	PV			•			•				•			shading
	ST tube		•							•				

PV: photovoltaik; PVT: hybrid collector; ST: solar themal collector; ○: system not in operation during the competition.

Table 5
Average PV system sizing in the European editions of the Solar Decathlon [12].

		2010	2012	2014	2019	2022
Installed power	kW_p	9.0	7.4	4.7	4.5	2.9
Installed power per floor area	W_p/m^2	184.5	131.1	69.2	67.3	29.9

resources. The triple goal of reducing the amount of individual living space (sufficiency), frugality regarding the use of energy and resources (efficiency), and the recirculation of the materials and products used (consistency) was demonstrated to the public by almost all the teams.

The all-electric demonstration houses on the exhibition site demonstrated a high level of energy efficiency, with almost all achieving an equalised or positive energy balance in the competition period. On average, 65 % of electricity consumption was covered directly or indirectly by solar power generation, 35 % by grid electricity. The simulation results of the design challenge show that it is much more difficult to achieve a positive year-round energy balance in retrofitted and extended multi-storey residential buildings.

Hybrid collectors used in conjunction with heat pumps became a central topic in order to best utilise the potential offered by the

Fig. 23. Rear side of a 250 W PVT module with integrated inverter (GRE).

Fig. 24. 375 W PVT collector with additional ambient air heat exchanger on the back (HBC).

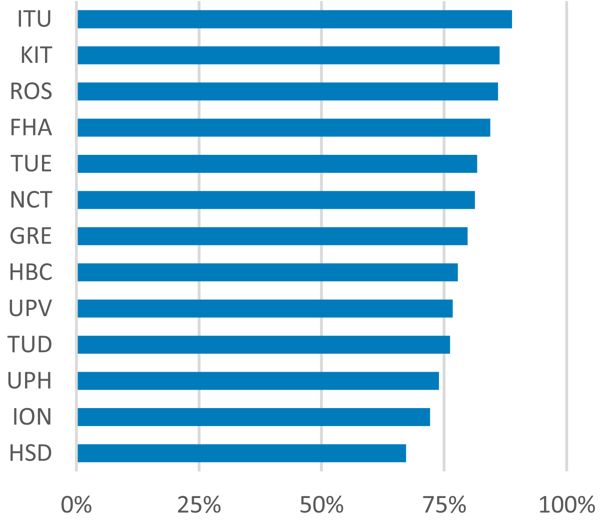

Fig. 25. Measured performance ratio I_{PR} of the installed PV systems incl. battery storage for 13 buildings during the two weeks of the competition.

small amount of roof area in urban constructions and to reduce or prevent noise emissions from the outdoor units of the usual air heat pumps. Due to the design of the competition and the monitoring applied, a performance analysis of these systems was not possible within the short period of the competition final. Individual follow-up research by the teams using PVT systems can contribute to filling this gap. Sophisticated solar systems in façades were added to the range of possibilities with respect to the need for a sufficient level of solar energy use in apartment buildings. Topics such as ventilated curtain walls, shading structures, coloured PV modules, new systems as well as cell technologies were presented with the aspiration to attain an appropriate architectural and technical integration. Both were achieved. On the one hand, individual formats and system solutions increase the costs compared with rooftop applications of standardised solar systems, particularly in the residential building sector. On the other hand, the goal of a net energy positive building requires sufficient solar yields.

The new focus of the competition on the renovation and extension of the existing building stock contributed to students and their universities becoming intensively involved with the dominant issues of the urban energy transition in Europe. What they have learned in the process will empower them in terms of the important tasks of the future. The experience they have gained ranges from the critical application of simulation works (SimRoom, co-heating test), to the perfection of the construction (air tightness, PV performance ratio), to the optimised operational management in connection with the power grid (energy flexibility), to name just a few examples. The more intense involvement of the students in the on-site measurements could help to increase the learning effects.

Much more intensively than in everyday university life, the students also learned how to convince experts of their concepts through facts, analyses, visuals and discussions (jury) and how to inspire people during the public tours of the buildings (visitors). Designing, planning, building and operating a house from start to finish in an interdisciplinary team is the unique and lasting experience of a Solar Decathlon participation [6]. Based on the outcome of IEA EBC Annex 74, the revised set of rules for the competition, the improved building documentation, the use of common simulation tools, the further development of the experimental set up and the extended monitoring all set new impulses. This concerns new disciplines and methods of measurement as well as the improved transparency and usability of the results. Since the SDE is not a research project, it remains to be seen whether the increased effort will be reflected in relevant research work by the teams after the competition. It remains an important task to encourage such efforts.

8. Outlook

All data and documents of SDE 21/22 are accessible on the "competition knowledge platform", where it can be further used for research and teaching purposes [5]. It remains to be seen how intensively the considerable number of associated possibilities are used in order to advance the academic teaching.

The follow-up project, "Living Lab NRW" [18], is based directly on the SDE 21/22, with 8 out of 16 houses from the competition final remaining on the solar campus in Wuppertal (refer to Table 2). The TUE project was transferred to a national living lab in the Netherlands, and many others are being used for research, education and presentation on their home university campus. The living lab NRW aims to achieve greater added value from the investments in the competition on site, as well as from the outlay of the teams. The synergy is clear. The target group work which started during the competition with school pupils, apprentices and students will be continued, and more time-efficient formats than with the SDE can be implemented. However, the initial experiences also show how different the requirements are when working with a house which must remain stable and functional at the competition site for 3 to 5 years, and the requirements for successful functioning

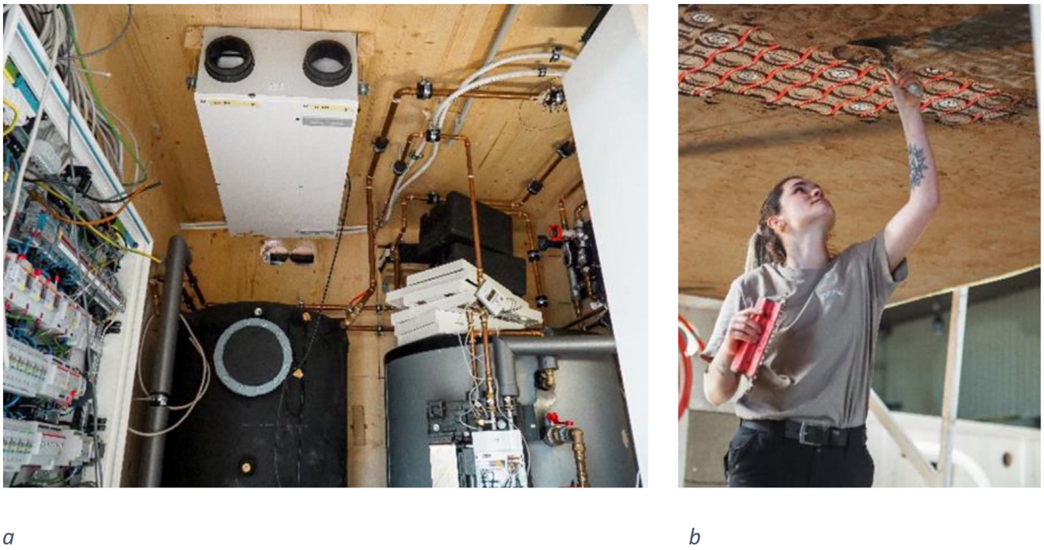
a b

Fig. 26. A) ice storage (in black) integrated into the student-built technical room of the FHA building. b) a student preparing the clay boards with thermal activation for the heating and cooling. © team FHA.

during the two weeks of the competition. To achieve this, the teams have to make early decisions, have preliminary structural consultations, make compromises and sometimes make constructional changes and improvements, including after the competition. An example of this is ensuring that the building is able to operate through the winter without succumbing to frost, and maintaining the secure function of the house automation. There would be numerous other requirements based on the respective construction law if the houses were to be lived in as normal. This is not the case in Wuppertal, as the focus here is on research and education.

Data availability

Data are available on the competition knowledge platform [5]. Furter data will be made available on request.

Declaration of Competing Interest

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

Acknowledgements

The authors thank the German Federal Ministry of Economic Affairs and Climate Action for funding the preparation and implementation of the Solar Decathlon Europe 21/22 in Germany under contract 03 EG B0019. Thanks to all the SDE 21/22 teams and the Energy Endeavour Foundation for their intensive and fruitful cooperation during all phases of the competition, from the start to the finish.

References

[1] homepage of the US Solar decathlon, https://www.solardecathlon.gov/ , latest visit 3.11.2022.

[2] I. Sartori, A. Napolitano, K. Voss, Net Zero Energy Buildings: A Consistent Definition Framework, Energy and Buildings, Elsevier, Oxford, 2011.

[3] Herrera-Limones, R., Rey-Pérez, J., Hernández-Valencia, M., Roa-Fernández, J.: Student Competitions as a Learning Method with a Sustainable Focus in Higher Education: The University of Seville "Aura Projects" in the "Solar Decathlon 2019", Sustainability 12 (1634), 2021, MDPI, 10.3390/su12041634.

[4] https://www.solardecathlon.gov/building-science.html, latest visit 13.1.2023.

[5] Building Competition & Living Lab Knowledge Platform, https://building-competition.org , latest visit 3.11.2022.

[6] Amaral, R., Arranz, B., Vega, S.: Participatory Research for the Evaluation of Satisfaction with Solar Decathlon Competitions: A Survey Analysis, Sustainability, vol. 13, issue 23, MDPI, 2021, https://www.mdpi.com/2071-1050/13/23/12995.

[7] J. Simon, E. Doris, S. Farrar, Insights on Technology Innovation – A Review of the U.S. Department of Energy Solar Decathlon Competition Entries 2002–2015, National Renewable Energy Laboratory, Golden, USA, 2017, Technical Report.

[8] Baghi, Y., Ma, Zhenjun, Robinson, D., Böhme, T. : Innovation in Sustainable Solar-Powered Net-Zero Energy Solar Decathlon Houses: A Review and Showcase, Buildings 11 (4), 2021, MDPI, doi: 10.3390/buildings11040171.

[9] E. Rodriguez-Ubinas, L. Ruiz-Valero, S. Vega, J. Neila, Applications of Phase Change Material in highly energy-efficient houses, Energy and Buildings 50 (July 2012) 49–62.

[10] Z. Ma, H. Ren, W. Lin, A review of heating, ventilation and air conditioning technologies and innovations used in solar-powered net zero energy Solar Decathlon houses, Journal of Cleaner Production 240 (2019).

[11] Cronemberger, L., Corpasa, A., Cerónb, I., Caama~no-Martínc, E., Vega, S.: BIPV technology application: Highlighting advances, tendencies and solutions through Solar Decathlon Europe houses, Energy and Buildings, vol. 83, Elsevier, Oxford, 2014.

[12] Voss, K., Hendel, S., Stark, M. : Solar Decathlon Europe – A Review on the Energy Engineering of Experimental Solar Powered Houses, Energy and Buildings, Volume 251, 15 November 2021 10.1016/j.enbuild.2021.111336.

[13] Vega Sánchez, S., Rodriguez-Ubiñas, E.: Science behind and beyond the Solar Decathlon Europe 2012 competition. Energy and Buildings, vol. 83, Elsevier, Oxford, 2014.

[14] K. Voss, K. Simon (Eds.), SDE 21/22 - The Competition Source Book, University of Wuppertal, 2023, https://doi.org/10.25926/7v9s-me45.

[15] Voss, K., Hansen, H., Kaliga, M., Kalpkirmaz Rizaoglu, I.: Solar Decathlon Europe 2022 - Bauphysikalische Ergebnisse von Demonstrationsgebäuden, Bauphysik Kalender 2023, published by Ernst & Sohn GmbH & Co. KG.

[16] homepage of the Solar Decathlon Europe 2021, postponed to 2022 www.sdeurope.uni-wuppertal.de, latest visit 17.02.2022.

[17] IEA EBC Annex 74 - Competition and Living Lab Platform, International Energy Agency, Energy in Buildings and Community Systems Programme, latest visit 3.11.2022.

[18] https://sde21.eu/living-lab-nrw, latest visit 3.11.2022.

[19] Climate Change Act 2021, German Federal Ministry of Economic Affairs and Climate Action, https://www.bundesregierung.de/breg-de/themen/klimaschutz/climate-change-act-2021-1936846 , last visited 24.11.2022.

[20] Rottschy, F., Müller, J. M., Voss, K.: Leichtes und nachhaltiges Bauen - Erfahrungen und Analysen im Kontext des Wettbewerbs Solar Decathlon Europe Bauphysik Kalender 2022, published by Ernst & Sohn GmbH & Co. KG.

[21] Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method (ISO 9972:1996, modified); German version EN 13829:2000.

[22] Building Energy Performance Assessment Based on In-situ Measurements, International Energy Agency, Energy in Buildings and Community Systems Programme, https://www.iea-ebc.org/projects/project?AnnexID=71, latest visit 30.11.2022.

[23] Lichtmess, M.: SimRoom 4 – A learning tool for dynamic space and energy balances, SDE 21/22 special edition, https://ingefo.de/Werkzeuge/SimRoom/, latest visit 3.11.2022.

[24] Kalpkirmaz Rizaouglu, I., Voss, K.: Building Performance Simulation to Stimulate Architectural Early Design, Proceedings of the 35th International Conference on Passive and Low Energy Architecture, A Coruna, Spain, 2020, 10.17979/spudc.9788497497947.

[25] Wege zum Effizienzhaus Plus - Grundlagen und Beispiele für energieerzeugende Gebäude, German Federal Ministry of Interior, Building & Community, 2018, https://www.bmi.bund.de/SharedDocs/downloads/DE/publikationen/themen/bauen/effizienzhaus-plus.pdf?__blob=publicationFile&v=6, latest visit 3.11.2022.

[26] Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems, International Energy Agency, Energy in Buildings and Community Systems Programme, https://annex82.iea-ebc.org/ , latest visit 30.11.2022.

[27] Solar Energy and Architecture, International Energy Agency, Solar Heating & Cooling Programme, https://task41.iea-shc.org/, latest visit 4.1.2023.

[28] Herb, S.V. et.al: A faster method for the simulation-based parametric optimization of structural shading, Proceedings of BauSim, Weimar, Germany, 2022.

[29] International Electro Technical Committee, „IEC 61724: Photovoltaic system performance monitoring guidelines for measurement, data exchange, and analysis“, 1998.

[30] Aslam, A., Ahmed, N., Qureshi, S., Assadi, M., Ahmed, N.: Advances in Solar PV Systems; A Comprehensive Review of PV Performance, Influencing Factors, and Mitigation Techniques, Energies 15(20), 2022, MDPI, 10.3390/en15207595.

[31] PVT Systems-Application of PVT Collectors and New Solutions in HVAC Systems, International Energy Agency, Solar Heating & Cooling Programme, https://task60.iea-shc.org/, latest visit 30.11.2022.

[32] Chhugani, B., Pärisch, P., Giovannetti, F.: Decarbonizing Heating Supply Systems in Existing Single-family Houses through PVT - Heat Pump Systems, Proceedings of EuroSun, Kassel, Germany, 2022.

[33] J. Schnieders, T.D. Eian, M. Filippi, J. Florez, B. Kaufmann, S. Pallantzas, S.C. Yeh, Design and realization of the Passive House concept in different climate zones, Energy Efficiency 13 (8) (2020), https://doi.org/10.1007/s12053-019-09819-6.

[34] H. Gholami, H.N. Røstvik, K. Steemers, The Contribution of Building-Integrated Photovoltaics (BIPV) to the Concept of Nearly Zero-Energy Cities in Europe: Potential and Challenges Ahead, Energies 14 (19) (2020), https://doi.org/10.3390/en14196015.

[35] Corti, P., Bonomo, P., Frontini, F., Mace, P., Bosch, E.: BIPV Status Report 2020. Building Integrated Photovoltaics: A practical handbook for solar buildings' stakeholders, Technical Report, BIPVBOOST project, 2020.

[36] Herrando, M., Ramos, A.: Photovoltaic-Thermal (PV-T) Systems for Combined Cooling, Heating and Power in Buildings: A Review, Energies, 14(19), Energies, 15(9), 2022, 10.3390/en15093021.