ANNEX 74

EBC

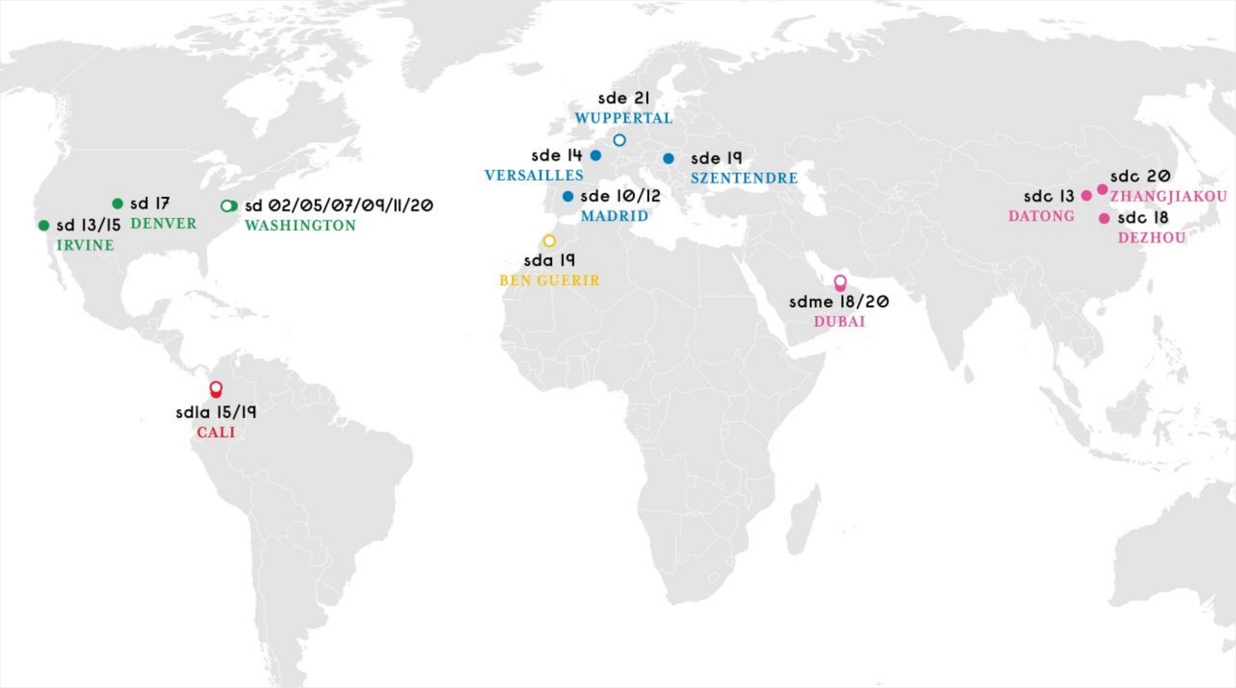
Energy in Building and
Communities Programme

International Energy Agency

Competition and Living Lab Platform (Annex 74) Science & Technology (Subtask A) Main Report

Energy in Buildings and Communities Technology Collaboration Programme

November 2021



Technology Collaboration Programme
by iea

International Energy Agency

Competition and Living Lab Platform (Annex 74) Science & Technology (Subtask A) Main Report

Energy in Buildings and Communities Programme

November 2021

Editors

Professor Dr Karsten Voss, University Wuppertal, Faculty of Architecture and Civil Engineering, Germany
(kvoss@uni-wuppertal.de)

Professor Dr Sergio Vega Sánchez, Technical University Madrid, School of Architecture, Spain
(sergio.vega@upm.es)

Contributing Authors

Prof Dr Karsten Voss, M.Sc. Andrea Balcerzak, M.Sc. Susanne Hendel, Dr Katharina Simon, M. Sc. Moritz Stark, Dipl.-Ing. Karl Walther, M.Sc. Jan Martin Müller
University Wuppertal, Germany
(kvoss@uni-wuppertal.de)

Joseph Simon, Architect, National Renewable Energy Laboratory, U.S. Department of Energy Solar Decathlon, USA
(Joseph.simon@nrel.gov)

Yuan Tian, Lucas Li, Solar Decathlon China, China
(yuan.tian@sdchina.org.cn)

Dr Samir Idrissi Kaitouni, Research Institute for Solar Energy and New Energies, IRESEN, Morocco
(kaitouni@iresen.org)

Sebastian Herkel, Fraunhofer Institute for Solar Energy Systems ISE, Germany
(herkel@ise.fraunhofer.de)

Prof Dr Jean-Philippe Bacher, Haute école d’ingénierie et d’architecture de Fribourg, Switzerland
(Jean-Philippe.Bacher@hefr.ch)

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the IEA Energy in Buildings and Communities (IEA EBC) Technology Collaboration Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The R&D strategies of the IEA EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. These R&D strategies aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five areas of focus for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)

Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems

Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: Deep Renovation of Historic Buildings towards Lowest Possible Energy Demand and CO2 Emissions
Annex 77: Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant Behaviour-Centric Building Design and Operation
Annex 80: Resilient Cooling of Buildings
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings

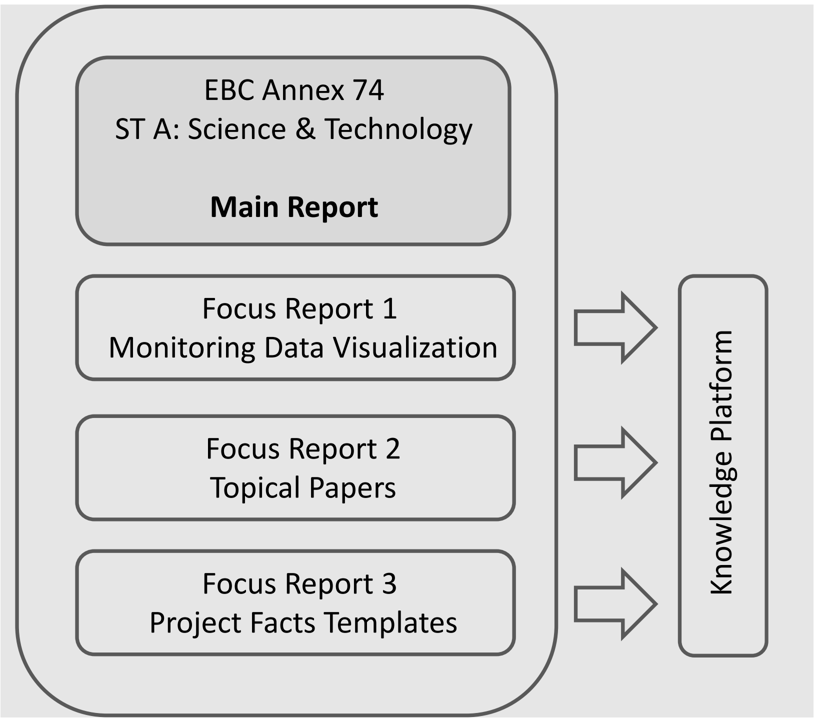
Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group - Building Energy Codes

Summary

The Annex 74 „Competition and Living Lab Platform“ ran between January 2018 und June 2021 within the Energy in Buildings and Communities Technology Collaboration Programme (EBC) of the International Energy Agency[1]. Annex 74 was intended as a platform mapping and linking the building competition and living lab experiences worldwide and working towards further improving existing as well as developing new formats. Annex 74 should stimulate the technological knowledge, the scientific level and the architectural quality within future competitions and living labs based on the development of a systematic knowledge platform as well as on the link to expertise from previous and current IEA activities[2]. A total of eleven experts from nine countries participated in this small Annex with varying degrees of intensity.

Four documents were produced as a result of subtask A "Science and Technology". This report is the main deliverable. This document is supplemented by three so-called focus reports:

- The focus report "Monitoring Data Visualization" contains for a better overview the graphical processing of the measurement data collected within four past Solar Decathlon competitions.
- The report under the title "Topical Papers" contains a set of thematic in-depth papers that link typical topics of the Solar Decathlon with research and practice issues, pointing out connections to IEA research networks.
- The documentation "Project Facts Template" presents a newly developed data collection structure for the quantitative data of buildings in a competition.



Structure of the documents generated by subtask A

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[1] https://annex74.iea-ebc.org/

[2] www.building-competition.org

After an introduction (chapter 1), the main report includes two extensive chapters with a review of the European editions of the Solar Decathlon between 2010 and 2019. 65 solar-powered competition buildings with numerous innovations were created in the four competitions. While chapter 2 focuses on building design and construction, chapter 3 focuses on energy engineering. Both chapters contain extensive cross-sectional analyses, tables and comparative graphs. Based on chapter 3, a comprehensive journal paper was published in the Energy and Buildings journal titled “Solar Decathlon Europe – A Review on the Energy Engineering of Experimental Solar Powered Houses” [voss 2011]. The presentation provides the background knowledge for the future development of the competition format. At the same time, it already shows which impulses have been introduced for the next edition in 2022 in Germany as a result of the analyses carried out. These include, among other things, the introduction of significantly improved documentation of the competition entries in terms of their characteristics and performance indicators. It has become apparent that the previous type of documentation was only suitable for cross-sectional analyses to a very limited extent. The focus report "Project Facts Template" documents the newly developed procedure in detail.

Together with the focus report "Monitoring Data Visualization", chapter 4 presents the different approaches for monitoring in the previous international competitions. This covers a selection of competitions worldwide. This selection helps to better prepare and systematize future tasks.

Chapter 5 contains the introduction and a compact presentation of the contents of the focus report "Topical Papers". This focus report comprises a total of 100 pages of information for the deepening of 11 individual topics.

A major concern within subtask A was the discussion of the question of the scientific benefit of building energy competitions such as the Solar Decathlon. Scientific work was and is partly done by the participating teams during or after the competition within their own university environment. The competition as a whole only allows this to a limited extent due to its boundary conditions. The rules practiced so far only allow for robust cross-sectional studies in exceptional cases. With analyses and discussions within the Annex, sub-areas could be identified in which a linkage with scientific work seems possible. For this purpose, proposals were developed in chapter 6, which have already been incorporated into the rules for the Solar Decathlon 2022. This concerns, for example, the PV system analysis (performance ratio), the building-power grid interaction (energy flexibility) and the comparison of simulation and reality of the thermal building behaviour (co-heating test). Chapter 7 presents recent activities on how research work can be continued at a central location on the respective competition sites within so-called "Living Labs" in the follow-up to competitions.

In total subtask A within Annex 74 gave the floor for a critical engineering focused review of past activities within the Solar Decathlon. A special focus lay on the European editions. Keeping competitions like this attractive in future must ensure to profit from lessons learned and from knowledge transfer. Together with the integration of new developments in architecture, construction and energy engineering attractive profiling of future events can take place. The experiments with the upcoming European event in 2022 will show how the additional scientific task can be matched successfully with a competition profile.

Table of content

1. Introduction[3]

1.1 Annex 74 structure and goals

Annex 74 is the IEA-EBC-based platform mapping and linking the worldwide competition and living lab experiences, working towards improving existing as well as developing new formats. Annex 74 intends to stimulate the technological knowledge, the scientific level and the architectural quality within future competitions and living labs based on the development of a systematic knowledge platform, as well as the link to know-how from previous and current IEA activities. With this in mind, competitions and living labs introduce new formats for the row of dissemination activities in IEA TCPs. The Annex is intended to be a think-tank with a focus on educating the next generation of architects and engineers through the use of university-based competitions and living labs. To address the specific Annex 74 objectives, the work is structured into three subtasks, with the knowledge platform as the common information resource and repository (Figure 1).

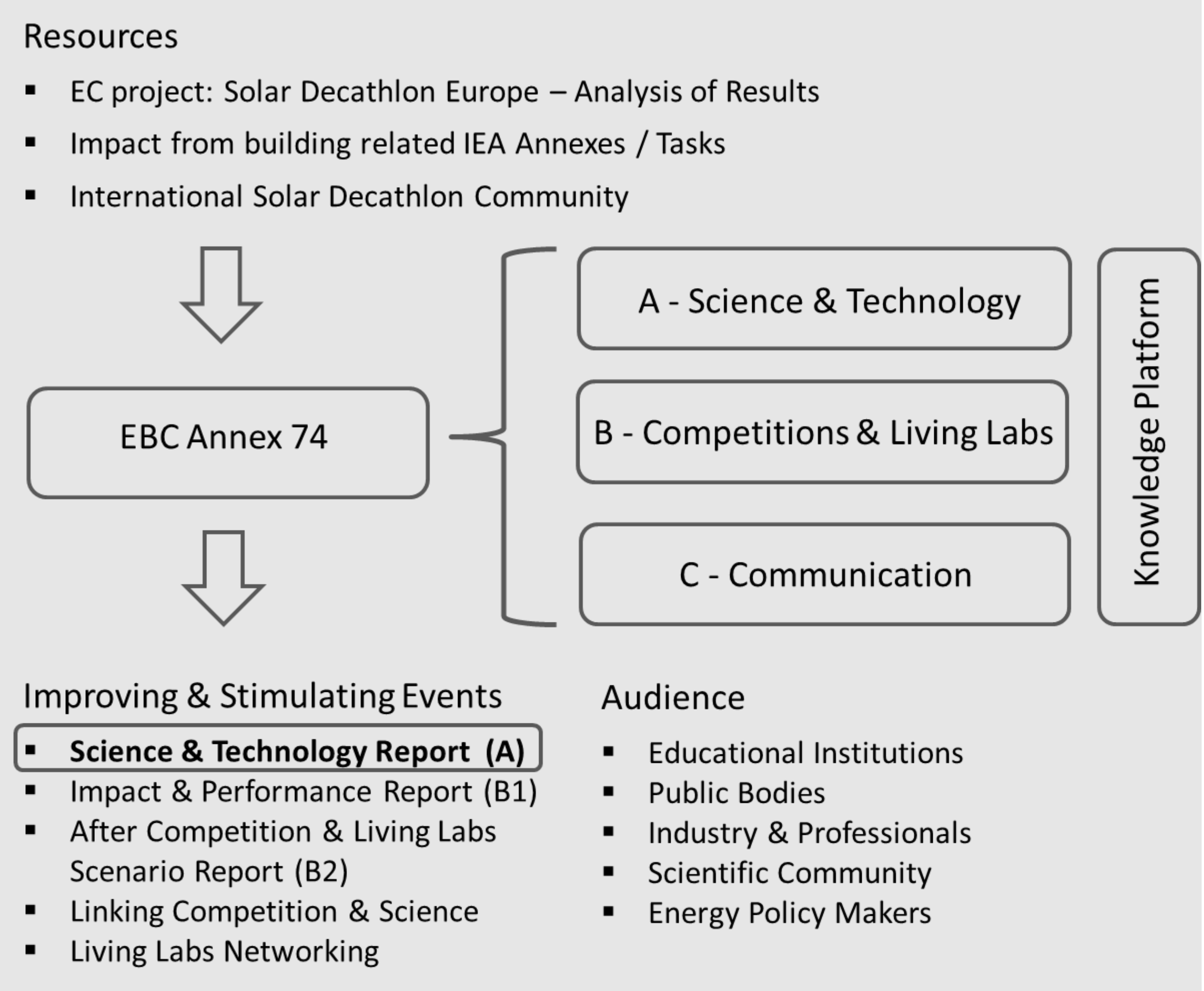

Figure 1: Structure of the Annex and its general workflow. The report presented here is the outcome of the subtask A on Science and Technology.

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[3] Author: Karsten Voss

The most significant output of the Annex is the profiling of future competitions and living labs, influenced by the collective work from participating experts and networks. A web-based knowledge platform is a main product for securing the experiences and data from the competitions and the instrument for the scientific analysis of the results. The knowledge platform addresses the teams, organizers, the scientific community and academic lecturers[4]. Interaction with the building related Annexes/Tasks within the IEA is planned to ensure knowledge transfer, especially through the incorporation of methods arising from other Annexes. Academic teaching will profit from the education material based on the competitions.

A European collaboration made up by parts of the Spanish, Dutch and German partners of the Annex 74 was set up for an application for an EC tender concerning the documentation and analysis work for the European Solar Decathlon[5]. The project “Solar Decathlon Europe Competitions - Analysis of the Results” had a three-year duration running almost in parallel to the Annex. Focus of the documentation and analysis were the five European editions of the Solar Decathlon until 2019 including SDE 21, which had been designated in 2019. The resources of the project feed into Annex 74. Besides individual national funding they become a main resource for the chapters 2 and 3 of this report.

The Solar Decathlon competitions have spread over the different continents, and are now entering into a new stage. New competition formats are under discussion as well. To acquire a more solid connection with research, the IEA EBC Annex 74 aimed to develop a framework to collaborate with existing and future Annex programs and integrate these research endeavours into future competition concepts. Given that there is a trend towards monitoring the houses for a more extended period of time (adopted in e.g. the Dubai 2018, China 2018, Morocco 2019, Szentendre 2019 competitions), there is a variety of test, monitoring protocols and sequences that may be implemented. Next to that, the living lab approach allows the adoption of a range of different tests in different research fields related to energy, indoor comfort, controls, user behaviour, life cycle assessment and building grid interaction. Competitions will also allow an assessment of the interaction of the different performance requirements at the same time.

1.2 Subtask A – Science and Technology

Objectives:

- Development of a framework that allows to implement a scientific track in the context of building energy competitions such as the Solar Decathlon
- To establish an overview of building physics research fields that would benefit from a collaboration with competitions for on-site full-scale living lab experiments
- To coordinate a joint initiative across IEA Annex programs to compile subsets of test protocols, monitoring protocols, and documentation templates for different research fields, test sequences, and measurement periods.
- Integration of subsets into a comprehensive multifaceted overview that provides a framework of research opportunities and boundary conditions to consider in future solar decathlon or related competitions.

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4 Source: Karsten Voss, Nathan Van Den Bossche, Sergio Vega, Peter Russell, Louise Holloway: Competition & Living Lab Platform, Official Annex 74 description, November 2017 http://annex74.iea-ebc.org/ /

5 EC Tender ENER/C/2016-502 “Solar Decathlon Europe Competitions – Analysis of the Results” performed by University Wuppertal, Technical University Madrid, Technical University Delft and The Energy Endeavour Foundation and coordinated by PNO Advies B.V. Rijswijk, NL

- To develop a network of excellence based on past, ongoing and future IEA Annex projects and to implement a continuous liaison between Solar Decathlon and other competitions and scientific research questions for which the concept of a competition can provide a relevant full-scale test environment.

The subtask was divided in the following activities, with some reductions due to the limited recourses available:

- Analysis of Experiences

Lessons learned were deduced by a cross-analysis of the methods applied and results achieved within former competitions using the knowledge platform (chapter 2, 3). The monitoring data from selected competitions were analysed on the level of single buildings as well the competition villages (chapter 4). This activity forms the core of subtask A work. Regarding Solar Decathlon Europe, this was done in close relation to the connected European-funded project "Solar Decathlon Europe - Analysis of the results".

- Mapping of research fields

Typical topics of architecture, engineering and research within past competitions have been mapped. So-called "topical papers" have been developed to link the competition tasks to knowledge from IEA expert groups (chapter 0). Contact was established to Annex 71 "Building Energy Performance Assessment Based on In-situ Measurements" with regard to share test methods and protocols for advanced building science to increase the relevance of future competitions.

- Aggregation of testing protocols, templates and guidelines

Test protocols and templates for future competitions are provided for practical implementation (chapter 6.1). These materials allow organizers of Solar Decathlons and similar competitions to stimulate building science with suitable rules and tasks based on proven knowledge.

1.3 Methodology

The work in the subtask on science and technology was based on the information resource of the knowledge platform as described in the project introduction. Data and information collection was performed in cooperation with the event organizers in the different countries and the teams participating. The visibility of information within this platform depends on the different rights per user group defined. Full information visibility and the ability to search and download information/data needs a protected login, to secure copyright issues[6]. A manual to operate the platform from the different user perspectives was developed and included in the platform[7].

The work in Annex 74 was intensively linked to the project "Solar Decathlon Europe - Analysis of the results", funded by the European Commission and performed by some experts of the Annex[8]. Its purpose was to provide the European Commission with an overview on the Solar Decathlon Europe (SDE) and transfer results for public visibility in the EC smart city information system: SCIS[9]. The extensive sections 2 and 3 within this subtask report are a direct outcome of this EC project. The work for these sections was performed under utilization of the knowledge platform complemented by direct contact to competition organizers and teams.

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[6] Contact the editor of this report in the case of a request for a login under the email: annex74@uni-wuppertal.de

[7] Building Energy Competition & Living Lab Knowledge Platform – User Manual, University Wuppertal, 2020, https://building-competition.org/

[8] "Solar Decathlon Europe Competitions — analysis of the results", as submitted by the consortium of PNO, Energy Endeavour Foundation, Bergische Universität Wuppertal, Universidad Politécnica de Madrid, and TU Delft in tender N° ENER/C2/2016-502

[9] https://smartcities-infosystem.eu/sites-projects/projects/sde-solar-decathlon

In all past competitions, monitoring of energy use, energy generation, house functioning and indoor comfort was performed. The main intention was the scoring of the buildings together with jury-based contests. Although the monitoring was not designed for scientific analysis, some analysis other than scoring is possible. This kind of analysis was performed for this subtask report, for example with section 3.6. The starting point was to understand the monitoring approaches used in the different competitions incl. the hardware applied, see section 4. The information was supplied directly by the competition organizers as far as possible. Data have been partly restructured, reformatted and error checked. All data available are stored in the knowledge platform for research purposes and graphical representations are part of sub report 1, adding to this main document. The analysis stimulates the design of the monitoring for future events and especially stimulates modifications to increase the scientific usability of the data.

Solar Decathlon Europe 21 (to be conducted in 2022 due to the worldwide pandemic[10]) will be the first competition directly stimulated by the work of Annex 74, namely subtask A. Templates are developed to collect and partly visualize all quantitative information of the demonstration buildings within a common format and platform to allow systematic documentation and cross analysis (section 6.2). It was found to be a major drawback in past competitions that such information was hidden in comprehensive text documents. Testing of the PV performance ratio was described and introduced into the competition rules as a first measure of investigation on the system level and not only the house level (section 6.3).

Another research task introduced is the investigation of the so-called performance gap between the simulation and the monitoring data regarding the thermal behaviour of the houses. Such a task needs controlled experiments (co-heating tests) to determine key performance indicators. It was the task of this Annex to learn from Annex 58/71 and discuss suitable procedures and perform simulations as well as real building testing for preparing the experiment during future competitions (section 6.5).

The student teams responsible for developing the demonstration units for the competitions or living labs may profit from a link to the information from external experts and especially the relevant IEA Annexes, tasks and working groups from the EBC and SHC and other Technology Collaboration Programmes. From this perspective, the experts of Annex 74 have decided to develop a set of so-called “topical papers” to describe selected topics relevant for the design of energy efficient solar buildings from the typology of Solar Decathlon houses, (see section 5 and the corresponding focus report 2). These topical papers are presented as part of the knowledge platform in a separate section on ‘teaching’ and complemented with a description of relevant calculation tools and useful links included[11].

1.4 Experience Resource – The Solar Decathlon[12]

The Annex 74 working environment from the early beginning was the Solar Decathlon. Established in 2000 by the U.S. Department of Energy, the competition first took place in 2002 and has seen over 20 editions worldwide until the date of this report, Figure 2. More editions are most likely to come.

The Solar Decathlon is a competition that the U.S. Department of Energy began organizing in 2000 (2002 being the date of the first competition event) for American universities, which consisted of designing and building a prototype of energy self-sufficient housing, powered by the sun, and equipped with all technologies that would allow maximum energy efficiency. The final phase consisted of assembling the houses on the National Mall in Washington D.C., where the so-called "Solar Village" was located, and where all the prototypes were exhibited and competed, passing through 10 different contests that comprise the competition (Decathlon). Its main objectives were to educate the next generation of architects and engineers as well as the general public, making them aware of the efficient use of energy, and promoting the development of integrated solar energy in houses.

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[10] www.sde21.eu

[11] https://building-competition.org/material

[12] Beatriz Arranz & Sergio Vega Sánchez, Universidad Politécnica de Madrid (UPM), Joe Simon, NREL

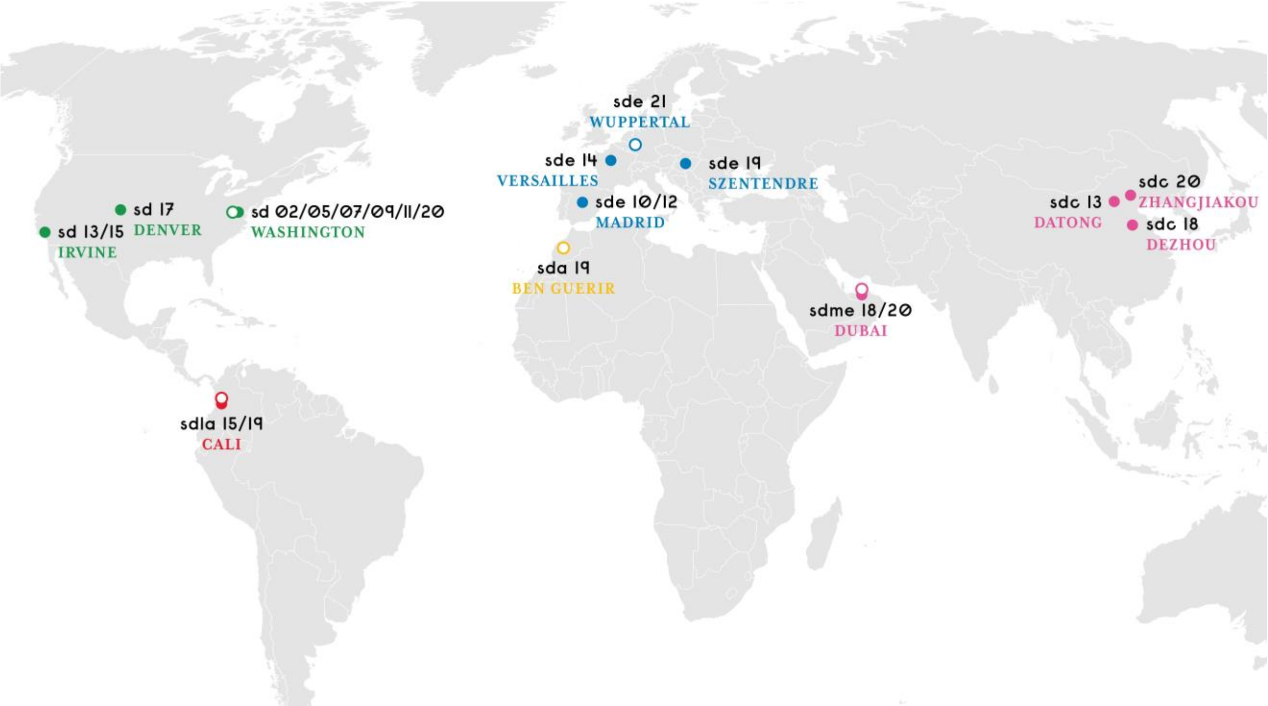

Figure 2: Map of the worldwide locations of the Solar Decathlon. Source: University Wuppertal

The U.S. Department of Energy Solar Decathlon showcases innovative solar-powered houses designed, built, and operated by collegiate teams. In summary, Solar Decathlon Competitions has proven to be a very effective tool to foster education, training and workforce capabilities development, and professional skills to the next generation of architects and engineers [annex 74 stb]. Teams are expected to demonstrate how the techniques, products, and solutions integrated into the prototype can significantly impact the residential housing market in the United States. Solar Decathlon offers students a unique opportunity for learning by bringing a project from concept to completion. The projects are to be developed by multidisciplinary teams, providing the opportunity to learn not only about technical issues but also about teamwork, communication skills, a sustainable lifestyle, and socio-economic issues in order to ensure the viability of their project.

For the students competing, the Solar Decathlon offers a learning opportunity rarely seen in academia. These design/build projects enable students to gain hands-on education that is immediately applicable in the workplace. The Solar Decathlon embodies much more than job training for students in a burgeoning industry, however. It represents a sincere effort on the part of students, teachers, industry professionals, and government leaders to solve some of the most pressing energy production problems facing our world. Collaboration is the key. The development of a student-built house rewards students that work in collaboration, blurring the traditional lines between engineering and architecture students to solve often difficult problems. To be successful, students have to reach out to design firms, builders, suppliers, and community leaders - for advice, support, and encouragement. Together, students, faculty, and industry partners find kindred spirits and learn from each other. With hundreds of houses built, the network-effect of the hands-on and industry-integrated learning continues to grow.

From planning to construction, it requires many roles to take a house from blueprint to reality. One of the key features of the Solar Decathlon is the realistic experience it provides to participating students. The Solar Decathlon is a uniquely large-scale university design-build competition, offering theory-to-practice opportunities for student teams. Ten contests evaluate various aspects of energy-efficient, solar-powered houses, which teams have spent nearly two years designing, refining, and building.

Going beyond a design competition to be a scientifically interesting design-build competition required a comprehensive evaluation of the house performance. Much like the athletic decathlon, the winner of the Solar Decathlon should not be only about a single metric (aesthetics or form), but a balanced accumulation measured performances. The house must function, and the student team must know how to operate the house successfully in order to win the competition.

Since the first event in 2002, the 10 contests have consistently been based on three guiding principles for the Competition:

- Supplying the energy necessary to live and work mainly using the global solar radiation incident on the structure during the contests,
- Exemplifying design principles that will increase the public's awareness of the aesthetic and energy benefits of solar technologies, which in turn increases the use of these design principles and technologies, and
- Stimulating accelerated research and development of renewable energy, particularly in the area of building science.

During the 2007 US competition, a Memorandum of Understanding (MOU) was signed between the Spanish and the American Governments, by virtue of which Spain would organize two editions of the Competition in Madrid, for European Universities, giving birth to the European edition. The Spanish Government commissioned the Universidad Politécnica de Madrid (UPM) to organize the first two editions of the competition in Europe, with the aim of adapting it to European sensibilities, and taking advantage of it to raise awareness and educate not only European university students, but also professionals and citizens, promoting energy efficiency, renewable energy, and the sustainability of our buildings and cities. The organizing team articulated two additional major objectives to be developed:

- To promote the innovation and generation of knowledge in systems to improve the energy efficiency of buildings, the integration of renewable energies, and the enhancement of the sustainability of cities and buildings, transferring all this knowledge to industry and professionals, in order to generate a critical mass of technicians who integrate it in their daily thinking, and can apply it in their designs and technical activity.
- To take advantage of the social interest and the media attraction that competition in the Media awakens, in order to sensitize society, from children and young people, to the general public, in a responsible use of energy, the need to improve the energy efficiency of our buildings, to integrate renewable energies, and to help develop a more sustainable world.

In order to meet the challenge and the proposed objectives, many changes and innovations were incorporated into the competition in Europe, and various strategies were developed, many of them shared with the participating teams, some favoured by the European Commission, and many of them extended and improved in the successive European competitions, to develop a competition clearly with a European character.

Focus of the review in the following two chapters are the five European editions of the Solar Decathlon until 2019 including consideration for Solar Decathlon Europe 2021.

2. Review Part I - Building Design and Construction[13]

Since the first Solar Decathlon Europe (SDE), energy efficiency in building design and construction has been a key part of the competition. Together, both form the so-called passive approaches for the reduction of a building's carbon footprint. Over the course of time, the competition in Europe has evolved from educating the general public on how to use renewable energy to "educate the general public about responsible energy use, renewable energy, energy efficiency and technologies available to help reduce their energy consumption" [sde14 2014, p. 1].

An essential innovation was the introduction of the sustainability contest during the transition of the Solar Decathlon to Europe in 2010. With that contest, a life cycle analysis and general sustainability considerations became part of the competition. This created a strong impact on the team's choice of materials and construction methods regarding resource efficiency and circularity.

Since the first edition of the SDE in 2010, 65 houses have been built until 2019. As the information was available, about 50 of these houses could be evaluated for the analysis included in this report. In some cases of analysis, fewer buildings were compared, but never less than 30 houses. Nevertheless, this number of comparable houses within one study shows in general the potential of the SD for research and as a source of lessons learned for the building industry. Careful and comparable documentation is a precondition but was not always achieved. There is still room for the betterment of this in future editions.

The information used for the following analyses was part of the final team documentation from past SDE competitions. Information on the building design and construction of all SDE houses is documented in the database: www.building-competition.org. Content will be continuously added to the database as it becomes available.

2.1 Solar Decathlon Europe Houses

Within the scope of this competition, international student teams design, build and operate these houses. To make the assembly, disassembly and transportation process possible, the houses are small, light-weight constructions. A high degree of prefabrication proved to be advantageous as the houses must be built in a short time frame and able to fully function immediately upon construction and without commissioning.

Usually, the houses run through the following process

- pre-construction at the team's home location,
- disassembly,
- transport to the event location,
- simultaneous assembly within two to three weeks,
- testing and demonstration for 10 to 14 days,
- again disassembly and in some cases transport back to and
- assembly either at home or a new location.

Some houses were moved more frequently than others, and, in some cases, houses act as a road show. For example, the house of the Virginia Tech University 2010 VGT ranked second in the SD 2009

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[13] Authors: Susanne Hendel, Andrea Balcerzak, Karsten Voss, University Wuppertal, funded by EC contract ENER/C/2016-502/SER/SI2.763962

competition. They also competed in and won the SD 2010 with a further evolution, the Lumen House. In between the two competitions, the house travelled in the USA and stood, among other places, on Times Square in New York City (Figure 3) and in Blacksburg Virginia. It continued to be exhibited in the USA after the SDE 2010 in Madrid, for example, in the Millennium Park in Chicago. With their house, this team demonstrated the communicational potential of an SD entry.

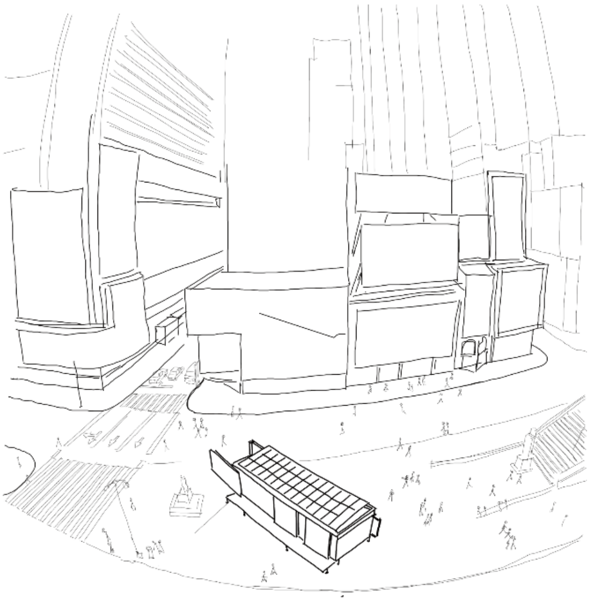

Figure 3: Sketch of “The Lumen House” on Times Square. This team presented their house at different locations in the US following their successful participation in SD 2009. Such events raise public interest outside the competition itself. Source: University Wuppertal, Susanne Hendel

2.1.1 Architecture

The SDE is a truly international endeavour. Competing teams from all over the world tackle European challenges within the framework of the competition and at the same time, reflect on their own cultural backgrounds and building traditions (Figure 4). Different interpretations of the same challenges and situations and different building traditions lead to a wide range of building designs.

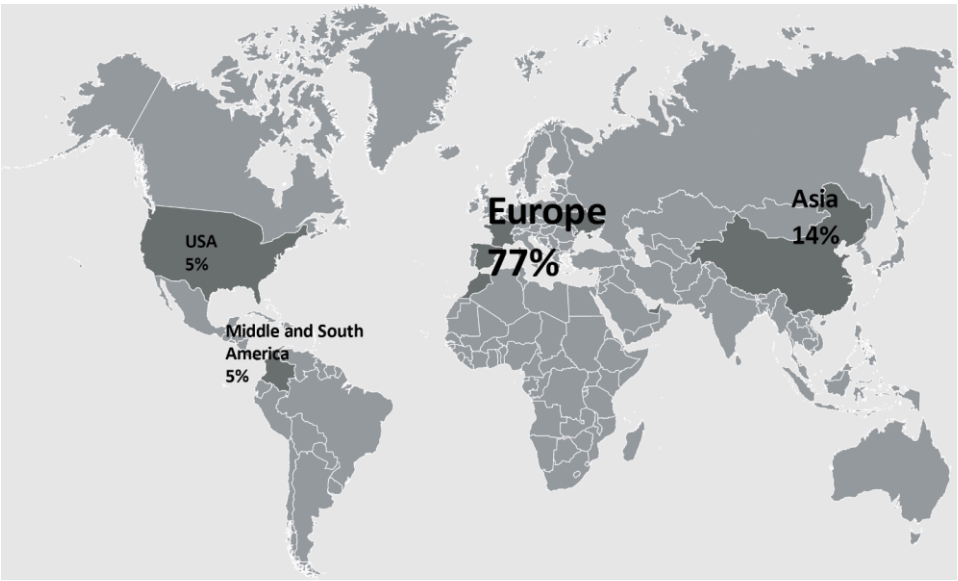

Figure 4: Distribution of the origin of the SDE teams 2010 to 2019. Beside teams from all over Europe, international teams stimulate the diversity of the design approaches. Source: University Wuppertal, Susanne Hendel

Unusual for architecture, most designs lack specific locations for their buildings and thus a specific building context. This fact is possibly one of the main reasons why awareness of the SD is still comparatively low in the public architecture discourse. Real architecture tasks reflect the context of a specific site and are judged in relation to that. With the introduction of specific construction tasks, some of the teams began to include context in the architecture task; examples of this can be seen in the SDE 2014 contributions made by the teams DEL (TU Delft), ROF (TU/UdK Berlin) and OTP (Frankfurt University of Applied Science)[14].The result is a significant new dimension within the current architectural discourse. In particular, the SDE 2019 houses represent this development, which will be consequently continued at the SDE 2021. At the SDE 2019, the team from the TU Delft built for their house MOR part of a reinforced concrete structure on the event site. The MOR team drafted a concept for the reuse of an office building in Rotterdam. A large part of this building's space should be used in future as living space. At the SDE site a residential unit was built to demonstrate this and recreated part of the existing reinforced concrete structure. The context is thus explained. However, the segment from the building is not easy to classify and appears unfinished due to the building task selected. Particularly suited is the innovative use of virtual reality to present the buildings in their contexts. It remains to be seen whether such approaches succeed in achieving greater visibility of the competition in the debate surrounding architecture.

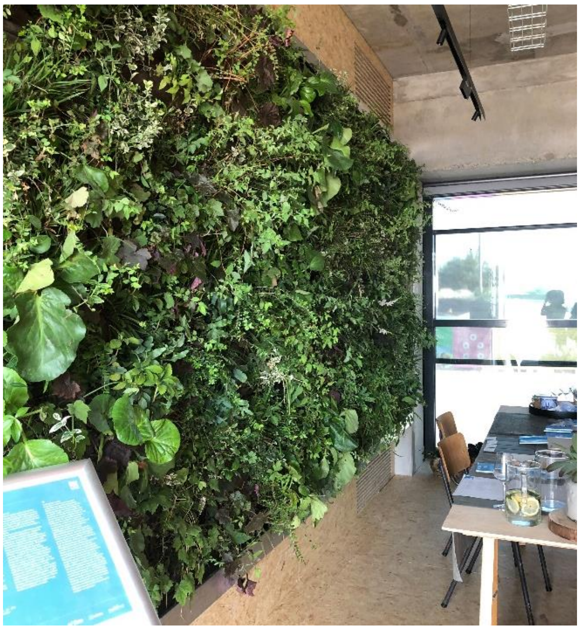

Figure 5: Interior view of the SDE 2019 TU Delft (MOR) house. The concrete structure of the existing urban building which is the starting point of the project is visible. Source: University Wuppertal, Katharina Simon.

A further significant architectural aspect is the size of the buildings. The houses are only about 60 m² in net floor area due to competition rules and the mobility required of the houses (refer to section 1.1.2). The small size of the buildings (Figure 6) leads to a multitude of architectural and interior design solutions for small rooms (refer to section 2.1.2). This is still uncommon in European building practice, but it is of increasing interest with regard to compact inner city living.

The integration of solar systems into architecture remains one of building practice's key tasks and a central design issue at the SDE. Apart from the presentation of standard systems such as on- and in-roof installations, numerous SDE projects have already contributed to improvements in the scope of solar systems within architecture (see chapter 2.4).

2.1.2 Building Size and Building Shape

The SDE gives impulses for compact and space-efficient living; the houses demonstrate options for innovative living spaces which are more space efficient than usual. As mentioned above, SDE houses need to be space efficient due to the size restrictions specified by the competition’s rules.

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[14] The abbreviations refer to the name of the teams within a competition, note the list at the end of this report.

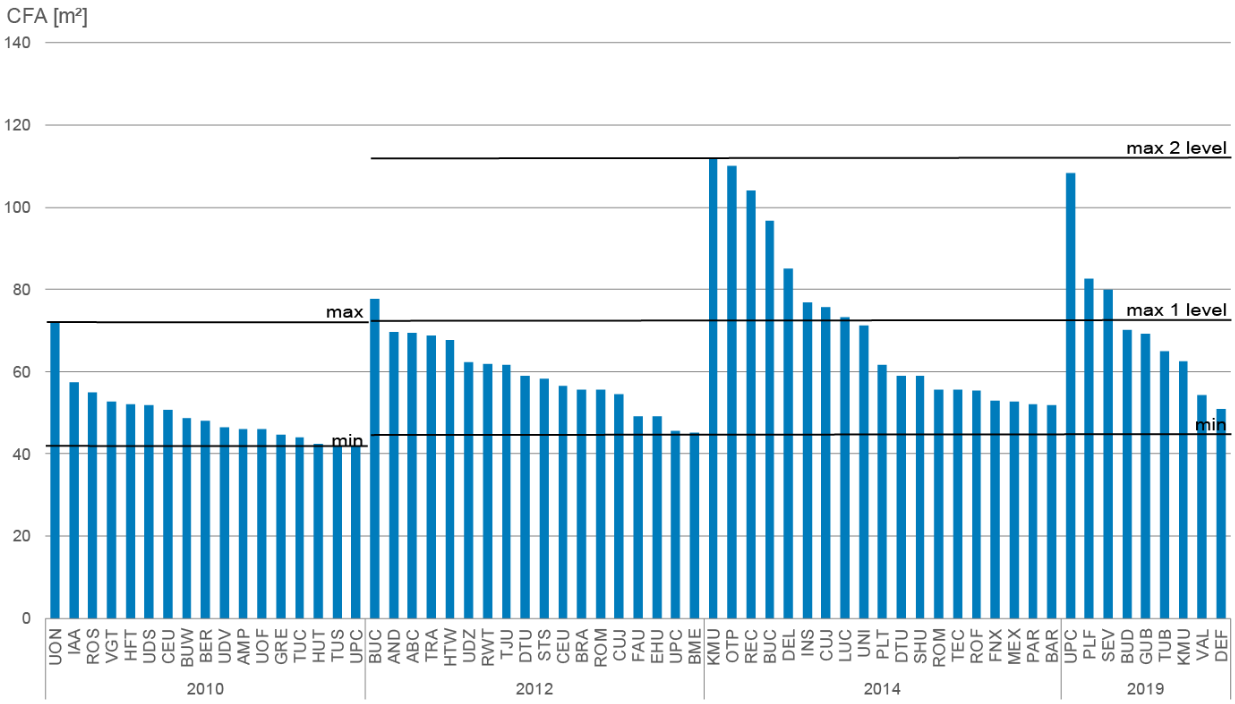

Figure 6: Conditioned Floor Area (CFA, as defined in the competition rules, almost comparable to the net floor area) of the SDE houses in the competitions from 2010 to 2019 together with the minimum and maximum building sizes given by the correlating SDE rules. The abbreviations refer to the team entries in each of the competitions. Source: University Wuppertal, Susanne Hendel

As the SDE is a competition between teams of students, the restrictions are created to ensure the feasibility of the building task. In order to ensure security and feasibility, the SDE houses have net floor areas between 42 m^2 and 74 m^2 (Figure 6) and in 2010 and 2012 most of the houses were one storey only. At the SDE 2014, as the maximum net floor area was extended up to 110 m^2, two storeys houses became common. The strict restrictions to the size of the buildings are also a result of limited space at the competition site, the need for short construction times and, as mentioned above, adherence to safety aspects during construction.

The aim is to design and evaluate houses for a two-person household; if the above-mentioned areas are taken into consideration, this corresponds to an average floor area between of 25 m^2 (2010) and 36 m^2 (2019) per person. In Europe in 2011, the average living area per person was about 43 m^2 [ec housing 2011], therefore, the area use of the houses is considerably denser.

Small buildings have more envelope area in relation to living space because of their unfavourable form factor. Figure 7 shows the surface to volume ratio, the -so-called form factor of exemplary SDE houses compared with two usual single-family homes (SFH). The two SFH chosen here represents the common form factor of homes in European building practice. Both homes were part of a research project for energy efficient homes in Europe [voss 2011]. The form factor of SDE houses is usually twice as large as that of standard European homes. However, the very low form factors of the houses 2014 DEL and 2014 MEX are outstanding. These low values can be explained by the fact that in 2014 a two-storey construction and a building size up to 110 m^2 net floor area was permitted. The two houses 2014 MEX and DEL with two floors were clearly more compact than the usual single-storey SDE houses.

This increases the buildings costs per floor area; however, it also increases the available area for solar systems in relation to the floor area.

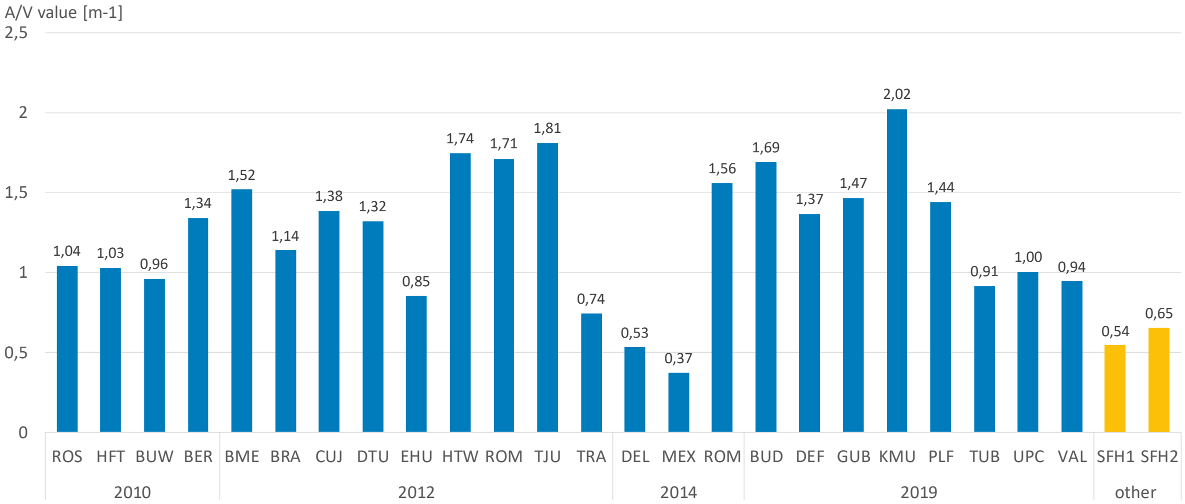

Figure 7: Form factor A/V of the SDE houses as listed by teams. To compare the form factors of SDE houses to houses in European building practice, two exemplary single-family homes from a German energy efficiency research project are also listed here (SFH1, SFH2). Source: University Wuppertal, Susanne Hendel

Besides the buildings' size, there are further restrictions with which the SDE houses need to comply. One of them is the so-called solar envelope. The solar envelope has the geometry of a square, truncated pyramid with a base area of 20x20 m, a height of 5.5 m and a roof area of 10x10 m [sde10 2010]. A maximum height of 6 m [sde12 2012] in SDE 2012 and 7 m [sde14 2014] in SDE 2014 were permitted. The solar envelope restrictions mainly guarantee un-shaded location of the buildings on the competition site in order to ensure fair competition.

Taking into consideration the building's design and habitability, the teams have to consider a space-efficient floor plan and building design. Space-efficient living concepts provide impulses for future living in European cities. Examples of space-efficiency are provided by the SDE 2010 teams, Wuppertal (BUW) and Berlin Living Equia (BER) and the 2012 Counter Entropy (RWT). The Wuppertal and the Counter Entropy examples show that space can be used multifunctional as storage. In the Wuppertal house, even the space underneath the steps of the stairs is used. The RWT building integrated storage space within the walls. The BER house demonstrates an open-plan design. The use of every space for storage as well as the creation of an open floor plan to maximize habitability is common in the SDE.

Figure 8: In order to create additional storage space, drawers are located under the stairs in the SDE 2010 BUW house. Source: SDE, Flickr, [sde flickr doc]

Figure 9: In the SDE 2010 BER house, all functions such as cooking, eating, living and sleeping have been combined in one room. Light bands in the walls and the roof symbolically separate the room into zones of use. Source: SDE, Flickr, [sde flickr doc]

Figure 10: As in the 2010 BUW house, the SDE 2012 RWT house also uses the construction areas for storage space. Here, cabinets and the kitchen are integrated into the walls. Source: SDE, Flickr, [sde flickr doc]

As the SDE houses lack an urban context, a number of experimental or extraordinary designs can be expected (Figure 11, Figure 12). Besides the most common rectangular floor plan, the SDE houses demonstrate a wide range of floor plan designs. Even circular (UDZ in the SDE 2012) or freeform floor plans (IAA in the SDE 2010) are possible, due to the lack of a site, district or urban context. In European building practice and particularly in an urban environment it would be almost impossible to adopt these more experimental designs.

Figure 11: The 2010 Fablab House is an example for an experimental building shape. Source: SDE, Flickr, [sde flickr doc]

Figure 12: The building shape of the 2012 Unizar house shows a circular floor plan with lots of consequences for interior furnishings. Source: SDE, Flickr, [sde flickr doc]

However, apart from a few examples, the statistics show that many of the SDE houses follow a simple cubature in the tradition of the “Bauhaus” movement of 100 years ago. Simple cubatures can have an economic advantage due to lower material use and construction time. Their presentation may also stimulate future European building practice.

A closer look at the design shows that most SDE houses have a rectangular floor plan. This is in contrast to the square or L-shaped floor plans more commonly used in Europe. Figure 13 depicts the floor and roof shapes of the SDE houses according to their frequency. Almost half of the houses have a rectangular floor plan; almost half of them have a flat roof. Together, they represent 30% of all the designs. Keeping in mind the above-mentioned solar envelope, its limited base and top shape and also the net floor area limitations, the teams needed to find a way to squeeze in as much space and as many functions as possible. The simple shape of a flat roofed building with a rectangular floor plan seems to be a safe choice for the teams.

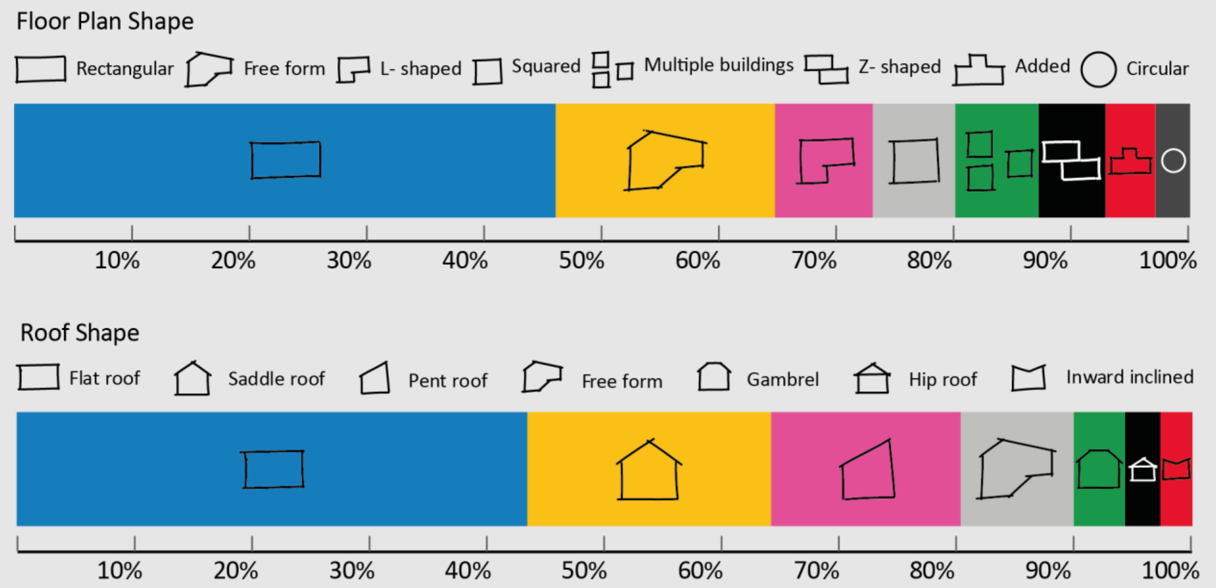

Figure 13: Floor plan shape and roof type of the SDE houses in SDE 2010, 2012 and 2014. Source: University Wuppertal, Susanne Hendel

Alongside the flat roof, almost 20% of the houses had a saddle roof and about 15% had a shed roof. Flat roofs are predominant in the SDE and become more usual in current building practice in Europe (new buildings) when no other roof shapes are stipulated by urban planning regulations.

Figure 14: The SDE 2012 winning team Canopea (TRA) built a convincing example of the upper floor of an apartment building. Source: SDE Flickr [sde flickr doc]

Utilizing optimum alignment enables the roof pitches of saddle roofs and pent roofs to be utilized for building-integrated solar systems. The CUJ house in 2012 and ROM house in 2014 are vivid examples of this. On the other hand, flat roofs bear the potential of optimal alignment of the solar systems to the direction and angle of the sun; the alignment on a flat roof can even be flexible to ensure a maximum energy generation all year long. In real building practice, flat solar systems have the advantage of being less sensitive to building orientation. In many cases, it is not possible to orient a sloped roof to the south. The SDE homes show both: solar systems were either elevated at an optimum angle and orientation (VGT 2010) or integrated flat onto the roof (HFT 2010, AND 2012). Solar Systems are one of the most dominant design elements in the Solar Decathlon homes. In contrast to usual practice, many SDE roofs are utilized for solar systems covering the entire surface area. The direct consequence is that green roofs or any kind of vegetation on the roof is not frequently applied by SDE teams.
The roof in the SDE is also a special element for interpretation. Some teams did not build just a freestanding single-family home but interpreted the task to build an addition to an existing building. Teams

like 2014 DEL, ROF and OTP are successful examples. The team DEL suggested a new exterior buffer zone to a standard Dutch single-family home (Figure 30). Small houses like the one presented by the DEL teams are common buildings in the Netherlands which are in need of energy modernization and space extension. The two German teams ROF and OTP from SDE 2014 also focused on urban challenges. Both suggested a new additional storey on top of an existing multi-level building. Their concepts suggest an increase in urban density through the vertical extension of existing buildings. This is highly adoptable in practice.

In conclusion, the SDE houses significantly differ from houses which are common in European building practice. As the houses are built within a student competition, they are significantly smaller and offer about 20% less living space per person, than is standard in the EU. The small size led to space-efficient housing concepts that can act as an inspiration, in particular for future urban living situations.

2.1.3 Architecture Scoring in the Competition

Architecture is one of the five core contests in the competition. Scoring is always carried out by an expert jury; the architectural understanding of the respective jury members corresponds to that in any architectural competition. The appropriateness of the architectural solution in order to fulfil the task chosen by the team is at the heart of the evaluation. As there are considerable differences in the tasks chosen, evaluation and comparison are difficult.

When the scores of the architecture contest are compared, the teams with the combined flat roof and rectangular floor plan solution were ranked in the first third. The most successful teams who had decided to use this form were VGT (first place in SDE 2010), ROS (second place in SDE 2010) and HFT (third place in SDE 2010), ROM (third place in SDE 2012) and ROF (third place in SDE 2014). In particular, the entire formal language of these houses was simple, easily accessible, but individually designed. Especially in a competition in which the jury only has a brief moment to evaluate the houses, a simple design language seems to be the most effective.

2.2 Passive Design

Passive approaches or passive technologies include all measures and design features to maintain or create a comfortable indoor climate without machines to generate heat or cooling from fuels, electricity or thermodynamic cycles. As stated in the SDE rules [sde12 2012, p. 32], all technologies that rely on a thermodynamic cycle are considered active and the use of fossil fuels are prohibited (resulting in all electric homes). Ventilation fans or circulation pumps, which are a frequent example, are not considered active technologies. Passive approaches are prioritised design strategies due to simplicity, user friendliness, durability and economic viability. Passive strategies often strongly interfere with architecture and therefore have to be considered in the early design phase.

Besides active solar energy utilization, SDE competitions have always focused on the use of passive approaches and their positive effect on comfort, efficiency and energy usage [sde14 2014, Para. passive period]. The so-called passive period was for the first time implemented in SDE 2012 and repeated in SDE 2014 and SDE 2019. Within this period of the competition, no active HVAC technology is allowed to run, but comfort has to be kept. In SDE 2021 its rules stipulate that, during the whole competition, buildings may only be operated in the passive mode [eef 2019-1, Para. passive period].

As mentioned above, all SDE houses are light-weight constructions with a lack of thermal inertia. The SDE 2012 took place in September in Madrid and SDE 2014 in June/July in Versailles. The teams of both competitions had to deal with air temperatures above 30°C (Figure 15, Figure 16). All teams had to find concepts either to cool their building or at least prevent it from overheating. The green and yellow box in Figure 15 and Figure 16 illustrates the comfort zones targeted by the rules. If the room temperature and humidity are within the boundaries of the green box, then the conditions are considered comfortable and the team would earn full points. For all measurements within the boundaries of the yellow box the team would earn reduced points and for every measurement outside these boxes no points would be distributed. The comfort zones are a scoring tool during the whole competition. During the passive period, only temperature comfort zones are in place [sde12 2012, Para. Appendix C: Passive Evaluation Period]. To show the general discrepancies between the climate during the event and the expectations based on the rules, temperature and humidity are both illustrated in Figure 15 and Figure 16.

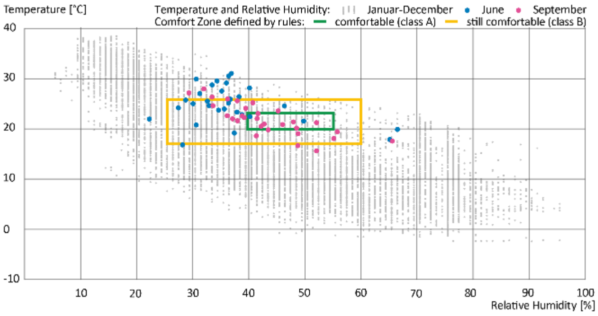

Figure 15: Annual weather data, including temperature and relative humidity of the SDE 2010 and 2012 event site Madrid. The weather data (long-term average) were exported from the Meteonorm database. Also illustrated are the comfort range for room temperature and relative humidity set by the SDE rules (boxes). Source: University Wuppertal, Susanne Hendel

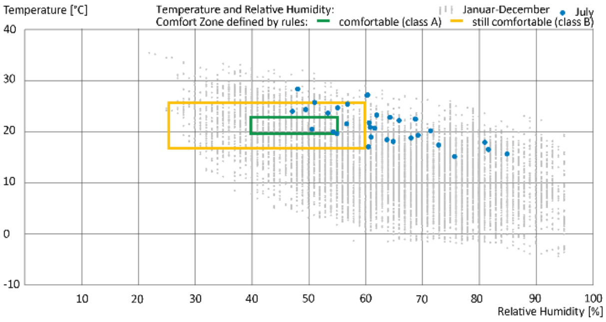

Figure 16: Annual weather data, including temperature and relative humidity of the SDE 2014 event site Paris. The weather data (long-term average) were exported from the Meteonorm database. Also illustrated are the comfort range for room temperature and relative humidity set by the SDE rules (boxes). Source: University Wuppertal, Susanne Hendel

2.2.1 Thermal Protection

Although the events take place in spring or autumn, SDE houses are designed for full year operation. This includes increased thermal protection to reduce the space heating demand as far as possible. Increased thermal protection is the major approach for energy saving, namely in the central and north European countries. The vast majority of the teams follow an approach with U-values of the opaque elements typical for low energy houses (≤0.2 W/m²) or even Passive Houses (≤0.1 W/m²K), Figure 17. This corresponds to insulation thicknesses of 16 cm up to 35 cm. By the use of innovative materials with reduced thermal conductivity (IR radiation absorption, aerogel, vacuum insulation, etc.) teams develop construction with reduced thicknesses. Most timber constructions are designed to minimize the timber fraction (TGI- beams, etc.) to avoid thermal bridges.

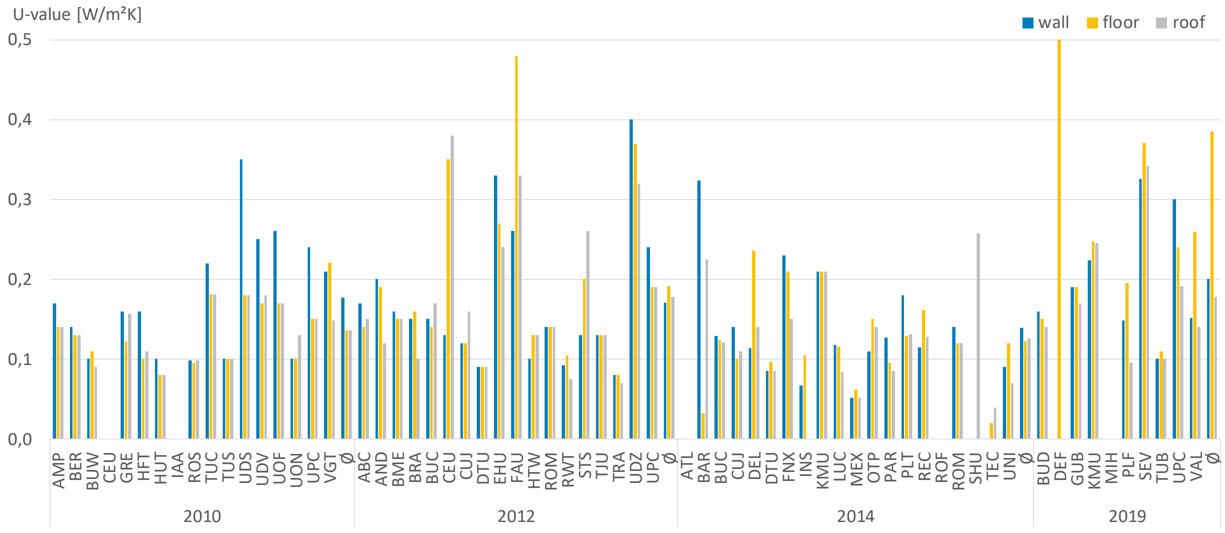

Figure 17: Comparison of the thermal transmittance (U-value) of the main construction elements of SDE homes based on the date given with the construction manuals. Source: University Wuppertal

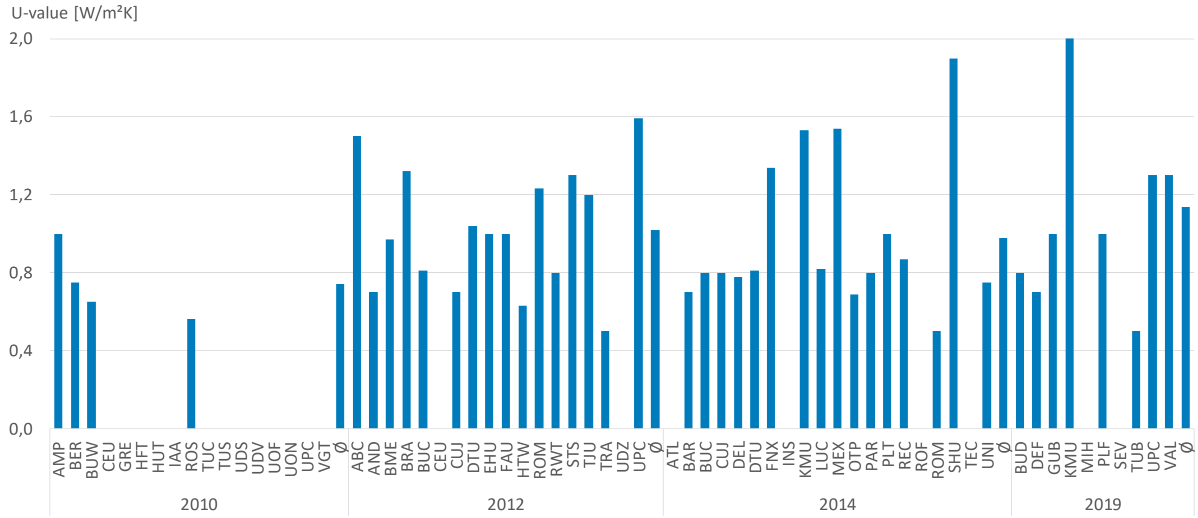

Figure 18: Comparison of the thermal transmittance (U-value) of the glazing applied in the SDE homes based on the date given with the construction manuals. Note: Whole window data including frame and spacers are not available. Source: University Wuppertal

Figure 19: Four-pane glazing at the SDE 2010 Finnish house (HUT - Luuku House). Source: University Wuppertal, Karsten Voss

Figure 20: Vacuum glazing at the 2012 Omoenashi House from the Japanese team CUJ. The vacuum double-glazing is combined here with a third pane to a triple glazing unit. Source: University Wuppertal, Karsten Voss

Glazing U-values below one are often realized, Figure 18. This typically corresponds with the use of triple glazing, coated glass and inert gas filling. The increased weight of such glazing has to be taken into account carefully in the whole window and façade design. Some teams show four-pane (SDE 2010 finish team HUT - Luuku House, Figure 19) or innovative vacuum glazing in their houses (2012 Omoenashi House from the Japanese team CUJ, Figure 20).

Testing the winter thermal protection was not a task in evaluation of the competition monitoring data due to the relatively high ambient temperatures during the events. Transmission losses or gains become a second order effect under these circumstances and measurement errors would increase. The level of thermal protection was considered as part of the jury evaluation on energy efficiency.

2.2.2 Windows and Shading

The proportion of window area in SDE houses is significantly higher than in common residential houses [voss 2011]. For example, the four German teams in SDE 2010 designed their houses with a window to envelope area ratio between 10% and 25% [detail 2011]. This corresponds to a window to floor area ratio of 40%. The higher proportion of windows is due to the small size of the SDE houses. Window sizes cannot be scaled down according to the floor area scaling without significant comfort and design losses. Many SDE houses pursue concepts with particularly large window areas. Larger openings visually connect interior and exterior spaces. This connection allows small interiors to appear more spacious (2010 BUW, Figure 21).

As the SDE houses have more window area per floor area and less thermal inertia compared to common buildings [detail 2011, p. 154], they run greater risk of overheating. The competitions took place in summer with moderate to high outside temperatures and solar irradiation with strict requirements for the indoor climate conditions. This situation made structural measures for overheating protection necessary in order to avoid large cooling loads. Efficient solar gain control through the application of any type of shading was crucial and carried out by all SDE teams, Figure 22. Solar gain control is currently of increasing importance in many European locations due to rising summer temperatures and lengthier hot periods as a result of global climate change. Demonstrating and testing effective and attractive shading in the competition entries can thus stimulate the market and raise public awareness.

Considering not only the location of the shading installed but also the way it works, several types of sun protection can be distinguished here. The general approaches are split up into a large variety of fixed or moveable systems (Table 1). Fixed systems such as the use of solar control glazing or overhangs (2010 HFT, 2012 RWT, 2014 ROM) operate without user interaction, thus, making solar protection secure. On the other hand, passive solar energy utilization is more (solar control glass) or less (overhang) reduced which results in increasing space-heating demands. External sun protection comprised moveable shading systems such as venetian blinds or screens (2010 VGT, 2010 BER, 2014 ROF) or curtains (2010 BUW, 2012 RWT). Moveable systems rely on building automation systems and/or operation by the user. Advanced automation systems might take into account weather forecasts and the adaptive learning of room utilization profiles. No limiting of passive solar gains in the heating season is the advantage of moveable devices.

The most effective systems are external devices such as venetian blinds, screens or shutters. They may block solar gains by 90% but at the same time, they block most of the view, depending on their positioning. Interior shading, for example by curtains, is much less effective (about 35%). Therefore, it comes as no surprise that external sun protection was applied by all SDE teams, but with a wide variety of system solutions. Only very few teams used rolling shutters, mainly because of their poor reputation among architects. Still, these are the most popular products in European residential building practice for reasons of noise protection, security and cost. From this point of view, the SDE homes are well suited to showcase advanced solar shading designs.

Figure 21: Windows are used to visually connect the small interior living space to the exterior. This way small interior spaces appear more spacious. Exemplary picture of the SDE 2010 Wuppertal (BUW) house. Source: Amparo Garrido

Table 1: Type of shading applied in SDE homes. The statistic is based on the team's deliverables and viewing of the house pictures. Shading systems here are divided into exterior and interior elements. The exterior elements are further distinguished into fixed elements like overhang or façade elements, that are built in front of windows or openings. Some teams apply PV modules as part of the shading devices. Source: University Wuppertal, Susanne Hendel

Year	Team	Exterior shading				Interior shading	Shaded roof
		Overhang	Fixed external	Moveable external	Added value	Moveable vertical	
2010	VGT			Sliding shutter		Curtain	X
	ROS	X		X			
	HFT	X		Curtain		Curtain	
	GRE	X		X	Solar system		
	HUT	X	Wooden elements				
	BUW			Curtain			
	AMP	X					
	UOF	X		Shutter	X		
	CEU	X	Façade elements	Curtain		Curtain	
	BER			X	Solar system		
	UDS	X		Venetian blinds			X
	TUS	X		Venetian blinds		Moveable vertical	
	UPC	X		Sliding shutter			
	UDV						
	UON	X	Façade elements				
	IAA	X					
	TUC	X		Shutter			
2012	TRA		Glazing integrated PV	Glazing integrated blinds			X
	AND	X	Façade and roof elements to shade patio				
	ROM	X					
	HTW	X		Curtain			
	RWT	X		Curtain			
	BME			Awning			
	CEU	X	Façade elements				
	UPC			Curtain			
	BUC	X		Shutter			
	DTU	X					
	TJU	X	Fixed wooden structure				X
	ABC	X		Doors	Solar system		X
	BRA	X		Venetian blinds			X
	EHU	X		Slides			

Year	Team	Exterior shading				Interior shading	Shaded roof
		Overhang	Fixed external	Moveable external	Added value	Moveable vertical	
	CUJ	X		Venetian blinds, sliding shutter			
	FAU	X	Fixed structure with PV	Doors	Solar system		X
	UDZ	X					X
	STS	X		Shutter			
2014	ROM	X		Sliding shutter	Solar system		
	DEL	X	glazing integrated PV		Solar system	Moveable vertical	
	ROF	X		Shutter	Solar system	Curtain	
	DTU	X	Façade elements				
	LUC					Curtain	X
	FNX	X		Venetian Blinds			
	OTP	X					
	BAR	X					
	CUJ	X					
	UNI		Glazing integrated PV	Sliding shutter	Solar system		X
	REC	X					
	MEX	X		Curtain			
	INS	X					
	PLT	X					
	TEC	X	Façade elements				
	KMU	X	Façade elements	Venetian blinds			
	SHU	X				Moveable vertical	X
	BUC	X					
	PAR	X	Façade elements				
	ATL					Curtain	
2019	BUD	X				Blinds	
	DEF	X		Rolling system			X
	GUB	X		Shutter			X
	KMU	X					X
	MIH	X					
	PLF	X				Curtain	
	TUB	X				Curtain	
	UPC	X		Shutter		Curtain	
	VAL	X		Slats			

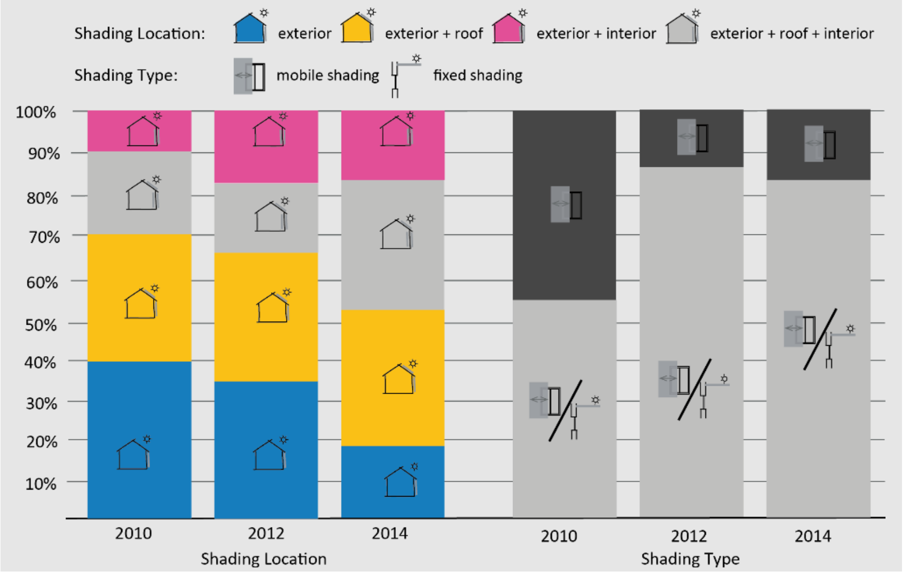

Figure 22 Distribution of external, internal, fixed and moveable sun protection devices presented by the SDE houses. Source: University Wuppertal, Susanne Hendel

Combinations of more than one shading system were also common in the SDE. External and internal shading devices were combined by 30% of the SDE 2010 teams, by 35% of the SDE 2012 teams and 45% of the SDE 2014 teams. In building practice, the combination of external and internal shading in the south of Europe is quite common, even necessary, while in central and northern Europe it is uncommon.

The shading concepts presented in the SDE can provide valuable input for building practice. Effective use of shading significantly improves the building performance during the hotter months. In Central and Northern European building practice, the boost to performance would be recognized as a gain in comfort and generally not seen as an energy-saving gain because active cooling is not yet common in residential buildings. Active cooling is quite common in Southern Europe, especially in hot humid climate; shading systems are always used in residential buildings. The focus on efficient shading is an important contribution to make the students and the visitors of the competition aware of the increasing role of summer thermal comfort considering the effects if climate change in Europe results in increased ambient temperatures and longer hot periods.

Apart from their effectiveness, shading elements are dominant design elements in the SDE houses. More than standard buildings, the SDE buildings are dominated by them due to their large window areas. Many of the shading ideas presented cannot be adopted by the building practice mainly due to the existing contexts and restrictions to which standard buildings have to adhere. However, with their design focus, some ideas certainly have the potential to inspire building professionals. Figure 23 to Figure 28 depict a few such examples.

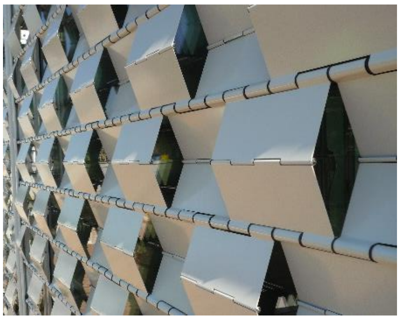

Figure 23: Moveable aluminum sun screen at the SDE 2010 ROS house. The profiles are specially folded to avoid direct light transmittance. The system as a whole is moveable from the bottom to the top and stored at the bottom of the façade. Source: University Wuppertal, Karsten Voss

Figure 24: View through an external curtain as a moveable sun protection device presented by the SDE 2010 Wuppertal house (BUW). A transparency of 7% is sufficient for visual contact. Source: University Wuppertal, Karsten Voss

Figure 25: Moveable vertical and external sun protection additionally used for solar power generation presented by the SDE 2014 ROM house. Source: SDE, Flickr, Valeria Anzolin, Jason Flakes [sde flickr doc

Figure 26: Overhang combine with external curtains at the SDE 2012 RWT house. Source: SDE, Flickr [sde flickr doc]

Figure 27:Fixed shading with integrated PV application and planting at the house of the team TJU at SDE 2012. Source: K. Voss, University Wuppertal

Figure 28: Foldable external sun protection additionally used for solar power generation at the SDE 2014 ROF house. Source: SDE, Flickr, Valeria Anzolin, Jason Flakes [sde flickr doc]

2.2.3 Buffer Zones

Buffer zones integrated into the floor plan enable the fully conditioned volume of a building to be reduced and thereby in some cases the energy demand for space heating. On the other hand, indoor thermal comfort of these spaces will be temporarily outside the comfort range during very cold or hot periods of the year, resulting in reduced utilization options. These limited utilization times have to be communicated to the occupants in order to avoid their misuse by fully heating or cooling such spaces with additional, mobile HVAC systems or by opening doors to the connected, fully conditioned rooms.

Buffer zones can be fully interior (interior buffer zone) like in an atrium house, fully attached (exterior buffer zone) such as a conservatory or a space within the construction layer like a ventilated façade (shell/ façade). Buffer zones may also serve as the upper or lower part of an apartment building to host communal spaces or allow for communal activities.

The variety of examples results from the different cultural background of the teams participating in the SDE. There are participating teams from countries with a long tradition in using buffer zones in architecture. The large variety of the approaches and designs presented raises public awareness of the use of non-conditioned and partially shared spaces for residential applications.

Special designs address building refurbishment. Typical market examples are post-war terraced houses with small living areas where a conservatory extends the space available during certain times of the year. Other examples are glazed balconies to reduce the thermal bridges in post-war apartment buildings with insufficiently insulated balcony ceilings.

The thermal insulation of a buffer zone envelope is typically less ambitious. This allows the use of "low-cost" materials or constructions such as greenhouses. Therefore, the building costs per volume are generally lower for buildings using buffer zones than for conventional buildings of the same total volume. Active solar systems might be integrated more easily in the buffer zone envelope than in the main building envelope as the requirements of thermal or sound insulation which have to be met are less strict. One such example is glazing integrated photovoltaics.

Buffer zones can be an integrated part of a building's ventilation concept in order to increase the comfort of the nearby zones. In winter, the zones may preheat the incoming air to the building by passive solar energy utilization. A typical solution is a conservatory (SFH) or a glazed balcony (MFH). Also, the zones may work as a solar chimney to increase stack effect ventilation for better summer thermal comfort. A special form of a buffer zone is the air gap in a ventilated façade construction, which may work to preheat the entering air or increase the ventilation by stack effect.

In the SDE context, buffer zones are well represented. Often, they are a credit to the vernacular architecture of the team's region of origin. Some teams develop new interpretations especially in interaction with active solar energy harvesting. Figure 29 gives an overview of the basic forms of the buffer zone buildings detected in SDE 2010 to SDE 2019. Table 2 lists the special functions of these buffer zone concepts for advanced low energy houses and their innovations. Selected examples from this table have been extracted with pictures to highlight the most innovative approaches. Innovations may cover:

- special market segments such as apartment buildings or the refurbishment sector,
- advanced functionality in the building's energy concept such as ventilation or solar system integration,
- special materials such as functional textiles, or
- added value of the space.

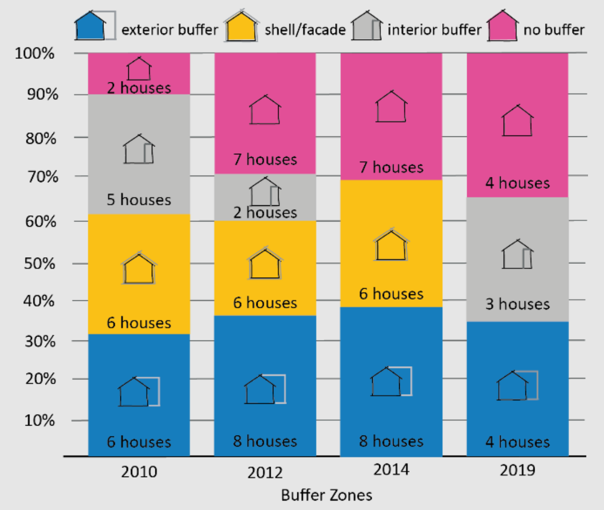

Figure 29: Number and type of buffer zones in past SDE competitions. The figure illustrates the frequency of the different type of buffer zones applied in and at the SDE houses. Buffer zones are distinguished here into exterior and interior buffers and buffer facades. Source: University Wuppertal, Susanne Hendel

Table 2: Types of buffer zone applied in SDE competitions 2010 to 2019. Source: S. Hendel, University Wuppertal

Year	Team	Building type		Building size		Ventilation Integration	Buffer Facade	Active Solar	Material Innovations	Added value
		New	Refurbished	Single family	Apartment building					
2010	VGT	X		X		X	X			
	ROS	X		X			X			
	HFT	X		X		X				
	GRE	X		X				PV		
	AMP	X		X			X			
	UOF	X		X			X			
	TUS	X		X						
	UPC	X		X				PV	Translucent façade	Foyer, Communal space
	UON	X		X		X				
2012	TRA	X			X	X		PV		Communal space
	AND	X		X		X				Patio
	ROM	X		X				PV		
	BME	X		X			X			
	CEU	X		X		X	X	PV		
	UPC	X		X		X		PV	Translucent façade	Foyer, Communal space
	EHU	X		X			X			
	CUJ	X		X			X			
	BRA			X			X			
2014	ROM	X			X		X	PV		
	DEL		X	X		X		PV		
	ATL	X			X			PV	Glass house	Stairwell
	LUC	X			X	X				Foyer
	FNX	X		X					Exterior curtain	
	OTP	X			X					Terrace
	DTU	X		X				PV	Glass house	Conservatory
	BAR	X		X		X	X		Translucent façade	Façade as solar chimney
	UNI	X			X	X		PV		Stairwell
	MEX	X		X			X		Curtain	Communal space, ventilated façade
	PLT	X		X		X				Multifunctional space
2019	BUD		X	X		X			Gabion wall	Conservatory
	DEF		X		X	X				Conservatory, Communal space
	MIH		X	X		X				Conservatory
	PLF		X	X					Interior curtain	Stairwell
	UPC	X							Curtain	Terrace
	VAL	X		X						Terrace

Figure 30: The attached conservatory at the 2014 DEL house with integrated solar systems demonstrates a buffer zone example for building renovation. Source: SDE, Flickr, Valeria Anzolin, Jason Flakes [sde flickr doc]

This example addresses the refurbishment of a typical post war Dutch terraced house. The new conservatory adds additional space to the typically small house and also creates the option of fully integrating active solar systems. The conservatory also takes part in the building's ventilation in order to reduce the energy demand of the house.

The approach shows large national market viability because of the multitude of comparable situations in the Netherlands.

Other outstanding examples for exterior buffer zones are the 2012 AND (Figure 31) and 2014 UNI houses (Figure 32). The 2012 AND house illustrated a different approach. The total conditioned volume of the house is separated into four zones. These zones are connected by a patio that is protected against precipitation but open to the environment for ventilation purposes. The conditioned zones are ventilated over the patio and profit in summer from the usually cooler air that passes through the patio. The patio is usually cooler than the environment due to the efficient shading and evaporative cooling combined with the natural ventilation which is in place.

An exterior buffer zone was added to the UNI home. The building service equipment, the community spaces and a laundry area are located in this zone. On the roof of this buffer zone, photovoltaic modules are fully integrated into the envelope. This space enlarges the total footprint of the building but because it contains necessary functions and is not conditioned but just ventilated, it reduces the conditioned volume of the building, which is separated from the unheated staircase.

Figure 31: Exterior buffer conservatory at the 2012 AND house, with advanced functionality for the building ventilation concept. Source: SDE, Flickr, Jose Luis Castillo [sde flickr doc]

Figure 32: Exterior buffer conservatory at the 2014 UNI house, with advanced functionality. Source: SDE, Flickr, Valeria Anzolin, Jason Flakes [sde flickr doc]

In addition, a temporary division of the bedrooms into a heated study and a cool sleeping area led to a functional gain. Problems have to be considered with respect to moisture transport from the warm to the cold sections and the associated dew point shortfall.

Curtains were not generally applied as external separation of buffer zones. The 2012 RWT and 2012 HTW teams used curtains to separate terraces directly adjacent to the building from their surroundings. The curtains protect these areas from high solar gains. These separated areas are nevertheless well ventilated thus protecting the rooms located behind them from overheating.

Figure 33: A coated curtain to temporarily create a buffer zone in the SDE 2019 PLF house. Source: University Wuppertal, Karsten Voss

Translucent facade elements as demonstrated with the 2010 UPC house create a shell that surrounds the internal conditioned zones (Figure 34). The external shell of the building is based on low-budget materials and constructions such as greenhouses. This shell combines precipitation protection, solar protection and active solar energy utilization. The house is still in operation as a teaching and research facility in the form of a living lab [living lab 2019] at the campus of the Catalonia Polytechnic. A comparable concept with the aim of direct market stimulation was demonstrated by the Cubity house as an out of contest project in SDE 2014 [cubity 2014]. Today, the Cubity prototype is used as a student dorm in Frankfurt, Germany, generating regular rental income.

The Canopea house at the SDE 2012 of the Team Rhone-Alpes (2012 TRA) shows the top floor of an apartment building as a buffer zone. The project (Figure 35, Figure 36) demonstrates the 10th floor apartment plus the buffer zone on top with its collective functions for the whole building. Photovoltaic modules are integrated into the entire roof surface of the glass roof of the buffer zone. These modules occupy a total area of 84 m^2 with nominal output of 8.7 kW. The other benefit of the buffer zone is its function as communal space which is of benefit to all residents of the house.

This type of communal space is also tested by the Cubity project (Figure 37, Figure 38). The Cubity project is based on a SDE 2014 connected development; the Cubity did not compete in the SDE but was a side project of the SDE 2014, which was presented out of competition at the SDE site in Versailles. Cubity demonstrates a house with minimal living space per inhabitant (7.2 m^2), shared spaces located in an unconditioned buffer zone, translucent façade and internal space separation with curtains. In Cubity the students share a kitchen, dining areas and lounge areas located in the buffer zone of the house. With respect to market stimulation, the Cubity project shows a promising development. The success of the Cubity project and especially the shared spaces concept led to a follow-up project the so-called Founder Lab [dstadt 2019], opened as a shared-space office building for young entrepreneurs. This type of development is a stimulating example for a direct market uptake from Solar Decathlon Europe.

Figure 34: A meeting house for a local district with a translucent façade at the SDE 2010 UPC house. The construction is based on typical greenhouse elements such as multilayer polycarbonate plates. Source: SDE, Flickr [sde flickr doc]

Figure 35: Exterior view of the Canopea house of the French 2012 TRA team. The unit demonstrated the upper floor with an additional buffer zone on top of an urban apartment building. Source: SDE, Flickr [sde flickr doc

Figure 36: Interior view of the 2012 TRA buffer zone. The roof integrates PV modules for solar power generation. Source: SDE, Flickr [sde flickr doc]

Figure 37: Exterior view of the Cubity house at its most recent location in Frankfurt. Source: University Wuppertal, Victoria Kunz

Figure 38: Interior view of the Cubity house. The image shows the communal kitchen which is located in the buffer zone of this house. Source: SDE, Flickr, Valeria Anzolin, Jason Flakes [sde flickr doc]

2.2.5 Passive Ventilation

In about 20% of the houses, there are designs and constructions for enhanced passive ventilation. Physically, the driving forces for passive ventilation are either temperature differences or pressure differences on the building envelope resulting from the wind. As the SDE homes only have one or two storeys they are generally not high enough to catch the wind. Pressure differences have to be increased by special designs such as solar chimneys.

The advantage of passive ventilation is in avoiding electricity consumption for the use of fans; the disadvantage of it lies in the complexity of the design and the controls. Designs such as solar chimneys or wind catchers become visible features of the architectural language. The automatic activation of openings to control the air flow creates the need for indoor and outdoor climate monitoring, rain guards and other features.

Passive ventilation is predominantly designed for moderate and warm climatic conditions and to prevent summer overheating and induce night ventilation by making use of the night-time ambient temperature drop. In cold climates, the need for ventilation heat recovery during winter favours fan-assisted solutions. Heat recovery can hardly be achieved with passive systems. The increased interest and market relevance of passive ventilation for summer thermal comfort may come about as a result of climate change in central European countries with rising temperatures and longer hot periods. They adopt approaches which have their origins in the architecture of southern regions. If a competition takes place in a hot climatic region, ventilation towers and solar chimneys play a bigger role than in Europe. One example of this is the Solar Decathlon Middle East in Dubai, 2018, or the Solar Decathlon Africa in Morocco 2019.

Table 3: Overview of the types of passive ventilation approaches applied in SDE competitions 2010 to 2019. Source: University Wuppertal

		Passive ventilation by		Visible architecture element
Year	Team	Stack/Chimney effect	Venturi effect	
2010	HFT	X	X	Solar chimney
	BUW	X		
	GRE		X	
	TUC	X		
	UDS	X		Solar chimney
	UON	X		
2012	AND	X		
	ROM	X		
	UPC	X		
	ABC	X	X	Solar chimney + roof element
2014	DEL	X		
	LUC	X		
2019	MIH	X	X	Solar chimney + roof element

Solar chimneys are a typical architectural element for making use of solar energy to power passive ventilations during day and night. The 2010 BUW, 2012 AND, 2014 DEL and 2014 LUC teams also utilized the stack effect for passive ventilation, but unlike the HFT solar chimney, these are not perceivable as construction technology and only use the given temperature differences in the houses. Examples of solar chimneys which shape the architecture of the house can be seen in the houses SDE 2010 HFT (Figure 39) and UDS (Figure 40).

The SDE houses have a low maximum height of less than 7 m [sde10 2010, Para. Solar Envelope]. The low height leads to low wind effects. Nevertheless, some of the buildings use visible elements to deliberately accelerate the air flow when the wind blows to create a vacuum for the building's ventilation (Venturi effect). Such elements were presented for example by the houses SDE 2012 Symbiosis (ABC) and 2019 Someshine (MIH) (Figure 41, Figure 42).

A detailed investigation of the benefits of passive night ventilation on the thermal performance of the competition buildings is not possible based on the monitoring data available. Measurements of the interior room temperatures during the so-called passive period are available for the SDE 2012 houses (Figure 43). These give an impression of the sum of all measures taken as no heating or cooling devices were used during this period. However, the available data does not enable an evaluation based on individual measures to be carried out. Figure 43 depicts the temperature curves of all SDE 2012 houses. The curves of the houses AND, EHU and HTW are highlighted in bold together with their trend lines as examples for potential differences.

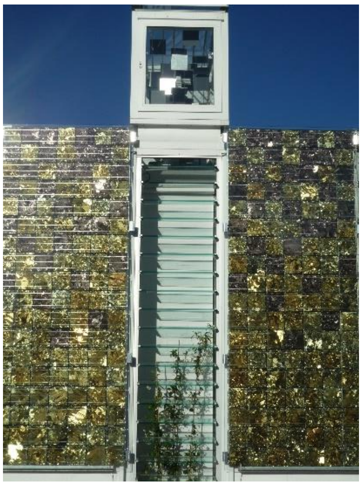

Figure 39: Solar chimney as part of the SDE 2010 HFT house. Source: University Wuppertal, Karsten Voss

Figure 40: Solar chimney at the SDE 2010 UDS house. Source: SDE, Flickr [sde flickr doc]

Figure 41: Roof construction with a Venturi wind catcher on the SDE 2012 Symbiosis house (ABC). Source: SDE, Flickr [sde flickr doc]

Figure 42: Roof construction of the SDE 2019 MIH house to use the Venturi- effect in addition to a solar chimney for passive ventilation. Source: University Wuppertal, Karsten Voss

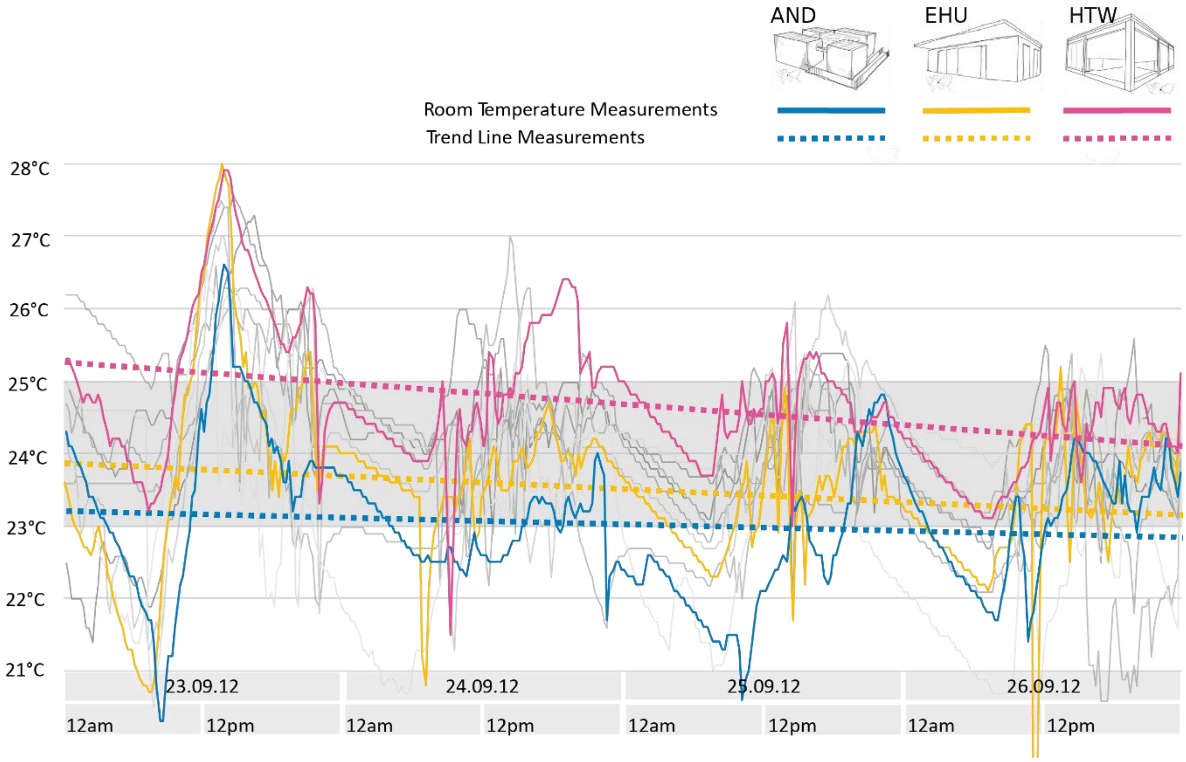

Figure 43: Comparison of the measured indoor air temperatures during the so-called passive period of all houses in SDE 2012. The curves for the three teams AND, EHU and HTW are highlighted with bold lines and added trend lines. The comfort range for full points is indicated by the grey field between 23°C and 25°C. Source: University Wuppertal, Susanne Hendel

As depicted in Figure 43, SDE 2012 houses mainly manage to keep their interior room temperature within the range defined as comfortable by the SDE 2012 regulations (full points) which lies between 23°C und 25°C [sde12 2012, Paras. 19, 5.1 Temperature]. The temperature level differs by up to 2° K between the houses which can also be seen in the starting condition at the beginning of the graphic. Special mention is made here of the 2012 AND house as it reached the lowest room temperatures on average. The 2010 HFT house which had on average the highest room temperatures had temperatures which were 2° K above those of the AND house. The temperatures of the EHU house lay in the middle between them. Especially the AND and HFT houses have significant differences in their use of passive strategies; the AND team combined fixed and mobile external shading with a central and passively ventilated buffer zone which is additionally cooled by evaporation. All living spaces border the buffer zone and were ventilated by them during the "passive period". The AND team concept was especially honoured by the energy efficiency jury. The HTW team, which had the largest temperature difference to the AND team, only focused on the use of shade in their passive concept; the HTW house combined an overhang with external curtains.

Table 4: Key data on the interior temperatures in the selected houses (from Figure 43) AND, EHU and HTW. The temperature limits for the comfort zone for interior room temperatures of between 23°C and 25°C complies with the specifications of the competition regulations. At the SDE, the teams won full points for temperatures within this zone. For temperatures between 21 – 23°C and 25 – 28°C fewer points were awarded.

Team	Lowest Temp	Temp below 22°C	Temp below 23°C	Temp. above 25°C	Temp. above 26°C	Highest Temp
AND	20.3 °C	13%	48%	3%		26.6 °C
EHU	20.3 °C		23%	6%		28 °C
HTW	21.5 °C		1 %	27%	9%	27.9°C

The potential of passive technologies for increasing building efficiency was examined by the energy efficiency jury. When they judged the houses, the jury had no information on the performance data as depicted in Figure 43. Thus, the award of points in the contest "energy efficiency" as an evaluation basis for the passive design is an independent addition to the comfort measurements. The purpose of this was for the contest "energy efficiency" to not only take into consideration passive systems but also active systems, the efficiency of the building envelope, the household appliances, the annual energy demand and the efficiency of the regulation strategies. Apart from the award of points, there is no other documentation of this contest.

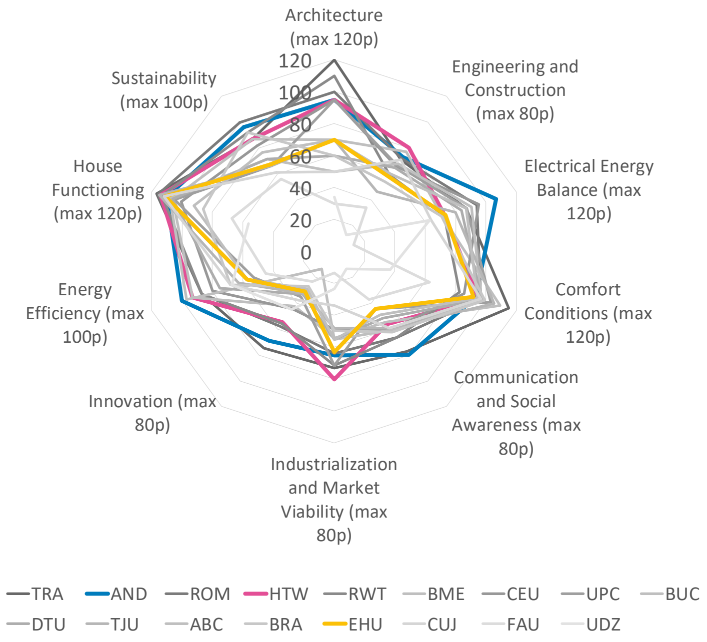

Figure 44: Spider diagram of the scoring of all contests and all teams in the SDE 2012. The three teams discussed above are highlighted. Please note that the contests don’t have the same maximum points. 100 points were the maximum result for energy efficiency contest and given to the AND team. Source: University Wuppertal, Susanne Hendel

Some teams, such as the AND team from the University Seville at SDE 2012 had deeply investigated the thermal performance of the ventilation for example by computational fluid dynamic simulations [terrados 2014]. It is a kind of disadvantage of passive ventilation approaches that the numerical investigation as part of the design phase becomes much more complex compared to fan-based ventilation. Therefore, planning is often based on “rules of thumb” and fans assist the ventilation as a kind of back-up approach in the case that strict indoor comfort requirements have to be kept.

2.2.6 Further Approaches

In the broadest sense, passive strategies and technologies can be understood as the optimization of the indoor environment without running heating or cooling devices. Plants, green spaces, water basins and evaporative cooling were implemented in the majority of SDE houses to make the microclimate around the building more comfortable. Water evaporation by ponds or plants lower temperature while increasing humidity. The application is suitable as long as humidity is not already higher than is comfortable. It is well-known that greened surfaces contribute to improving the microclimate and air quality as well as buffering heavy rain water. Examples for the integration of vegetation, wetlands and evaporative cooling devices into the building's design are shown by Figure 45 to Figure 48. Such approaches were proven to work well, for example, in SDE 2010 and 2012 in Madrid with its warm but dry climate: in the 2012 AND house, stone slabs which were constantly flooded with water were installed into the external areas between the parts of the building. The 2010 GRE team relied heavily on the use of outdoor plants to regulate the microclimate. The integration of vegetation into the design of a building can be further promoted in future competitions as well as in European building practice, especially if the focus is on urban situations.

Figure 45: Evaporative cooling at the SDE 2010 site. Source: University Wuppertal

Figure 46: Combination of water and vegetation into the building design at the SDE 2010 VGT house. Source: SDE, Flickr [sde flickr doc]

Figure 47: Integration of water basin into the building design of the SDE 2010 BUW house. Source: SDE, Flickr [sde flickr doc]

Figure 48: Green façade at the SDE 2010 AMP house. Source: SDE, Flickr [sde flickr doc]

Almost all teams in the SDE paid special attention to the air tightness of their building envelope. This optimization of the building envelope doesn't only help to maintain a comfortable indoor temperature especially during winter in colder climates, but also increases the efficiency of active cooling. For the efficient use of supply and return air ventilation and especially with regard to heat recovery, an air tight building envelope is mandatory.

2.3 Constructions and Construction Materials

Construction materials for small homes were traditionally selected on the basis of the local availability of resources and climatic conditions: whereas timber constructions are typically applied in the north of Europe, massive constructions dominate the housing stock in central and southern Europe. Buildings in the south particularly profit from the thermal inertia of massive constructions to buffer the summer temperature swing between day and night and allow for thermal comfort without active cooling. In most cases, thermal inertia is not significant for the space heating demand of a building. That makes light-weight buildings more suitable in heating dominated climates.

Prefabrication is a typical property of timber constructions and can be elementary building or modular building. The higher the degree of prefabrication is, the shorter the building assembly time is on site. The prefabrication and short assembly times are the major arguments why most buildings for the Solar Decathlon Europe are timber frame houses. Typical assembly times are between 10 and 14 days with some night-time assembly. In general, timber constructions are easier to assemble and problems with the mismatch of building elements at the junctions can be more easily solved by non-professionals. It is important to keep in mind that the houses at SDE are mostly built by students, most of whom have no practical training in the building profession.

Table 5: Overview of the degree of prefabrication of the SDE houses and the main load bearing materials. The lowest degree of prefabrication is prefabricated parts like columns or beams which are not listed here because all teams used them. The next higher degree is prefabricated elements like walls and the highest degree of prefabrication means that whole rooms or building segments ("modules") are prefabricated. Listed here are only those teams which chose to prefabricate at least elements of their building. Source: University Wuppertal, Susanne Hendel

		Prefabrication type		Main Construction Material	
Year	Team	Elements	Modules	Wood	Steel/ Metal
2010	VGT		X	X	
	ROS	X	X	X	
	HFT		X	X	X
	BUW	X		X	
	CEU	X		X	
	GRE	X		X	X
	HUT	X		X	
	IAA	X		X	
	TUC	X		X	
	UDS	X	X	X	X
	UDV	X		X	
	UON	X		X	
	UPC	X	X	X	X
	AMP		X	X	
2012	TRA	X	X	X	X
	AND		X	X	
	ROM	X		X	
	HTW	X		X	
	RWT		X	X	X
	BME		X	X	
	CEU		X	X	X
	UPC	X	X	X	X
	BUC		X	X	
	DTU	X	X	X	
	TJU	X	X	X	
	EHU		X	X	
	ABC	X		X	X
	BRA	X		X	X
	FAU	X	X	X	X
	STS	X		X	

		Prefabrication type		Main Construction Material	
Year	Team	Elements	Modules	Wood	Steel/ Metal
2014	ROM	X		X	
	DEL		X	X	X
	ROF	X		X	
	LUC	X		X	
	FNX		X	X	
	DTU	X		X	
	REC		X	X	
	CUJ	X		X	
	OTP	X		X	
	MEX		X		X
	PLT	X		X	
	KMU	X		X	
	SHU	X		X	X
2019	DEF	X		X	
	GUB		X	X	
	KMU	X		X	
	MIH	X		X	
	PLF		X	X	
	SEV		X		X
	TUB	X		X	
	VAL	X		X	

The majority of the teams chose a design with prefabricated elements such as walls and roofs (55%), fewer went for modular designs (35%). This is mainly due to a lack of knowledge on modular building, transportation size limits and the design limitations for ensuring the load statics of each module. For the same reasons, modular designs are not that common in Europe but are currently a topic of investigation. The main reason for this is the search for measures to lower relatively high construction costs [detail 2016].
The 2002 EU Energy Performance of Buildings Directive and its two modifications have increased the thermal property requirements of the building envelopes of new buildings in Europe. This results in more thermal insulation and more airtight buildings. Indoor prefabrication in a workshop is an essential approach to ensure such qualities at a reasonable cost level. Students at the SDE are trained to design and build prefabricated homes. They are ready to apply their knowledge in their future professional activity in an expanding market. Today, the market share of prefabricated timber homes is more than 40% in Scandinavia and more than 20% in Germany [schober 2018, p. 9]. There is room for an increase in this market share in Central Europe in comparison with the US market which has been fully dominated by prefabricated houses for decades.
The type of construction and materials used are important for the sustainability rating and the circularity potential of a building. A sustainability contest was introduced for the first time when the competition was transformed from the US to Europe. This reflects the market introduction of sustainability ratings [dngb 2019] which cover more than the energy use in a building and include, in particular, life cycle carbon footprint and circularity.
Figure 49 shows the SDE 2010 Sunflower house (TUC) on day nine of assembly at the event site. In 2010, the teams had a total of 17 days to assemble their houses [SDE 2010 site operation plan]. In order to shorten the construction time at the event site, the 2010 TUC teams chose to prefabricate elements of their house; in Figure 50 the wall elements are already installed. The team finished construction in time. The

SDE 2010 overall winner, the VGT team designed and pre-constructed modules of their house in maximum transport sizes. Figure 50 shows the delivery of the main module on the night of day seven of assembly. This main module was supplemented by building elements such as the exterior shading, deck elements and the solar systems that were mounted on the roof. This team had one of the fastest assembly times on site. This building was also optimized for mobility and was assembled within a few days on Times Square in New York and later in Chicago.

While in the SDE 2010 only 6 out of 16 teams used modular designs, in 2012 the number of teams increased to 11 out of 18. One of the 2012 teams was the Spanish team from Seville with their house Patio (2012 AND). Figure 51 shows the delivery of one of the room modules during the assembly phase of the competition. The prefabrication of entire room modules is the logical consequence of the building design as the rooms are separate from each other and only connected by a non-conditioned patio. The advantages of this design and the patio is also described in the chapter on the buffer zones.

In order to examine the construction of the SDE houses, a distinction is made between the load-bearing main construction, the surface cladding inside and outside, the insulation and materials with room climate regulating properties.


Figure 49: Construction of the 2010 TUC house on day nine of assembly at the SDE 2010 event site. Source: SDE, Flickr, Javier Alonso Huerta [sde flickr doc]


Figure 50: Arrival of one of the modules of the 2010 VGT house at the event site on day seven of assembly. Source: SDE, Flickr, Javier Alonso Huerta [sde flickr doc]

Figure 51: Arrival of one of the modules of the 2012 AND house at the event site. Source: SDE, Flickr [sde flickr doc]

The construction of the houses is very important for the acoustic properties, namely the sound insulation. The insulation level depends on the window and door ratio, the air tightness and the sound insulation properties of the opaque and transparent elements including their joints. Sound insulation is an ambitious task with respect to the light constructions. The sound insulations were tested with separate measurements in the two Spanish editions of the SDE, Figure 52 [madrid 2014].

Acoustics experts have been responsible for choosing the façade of the houses on which the tests are carried out. Measurements were made on the most unfavourable façade. The measurement was done by the organisers according to the global method proposed in the ISO 140-5:1998. The sound insulation Dls,2m values in decibel (dB) for each of the 1/3 octave bands are calculated between 100 Hz and 5 kHz. Calculations have been done according to ISO 717-1:1996. All available points are earned above 42 dB. No points are earned if the acoustic value is equal or below 30 dB. Three teams in the competitions received a high sound insulation above 42 dB, most teams manage to keep within the limits, but still some constructions fail with their acoustic performance.

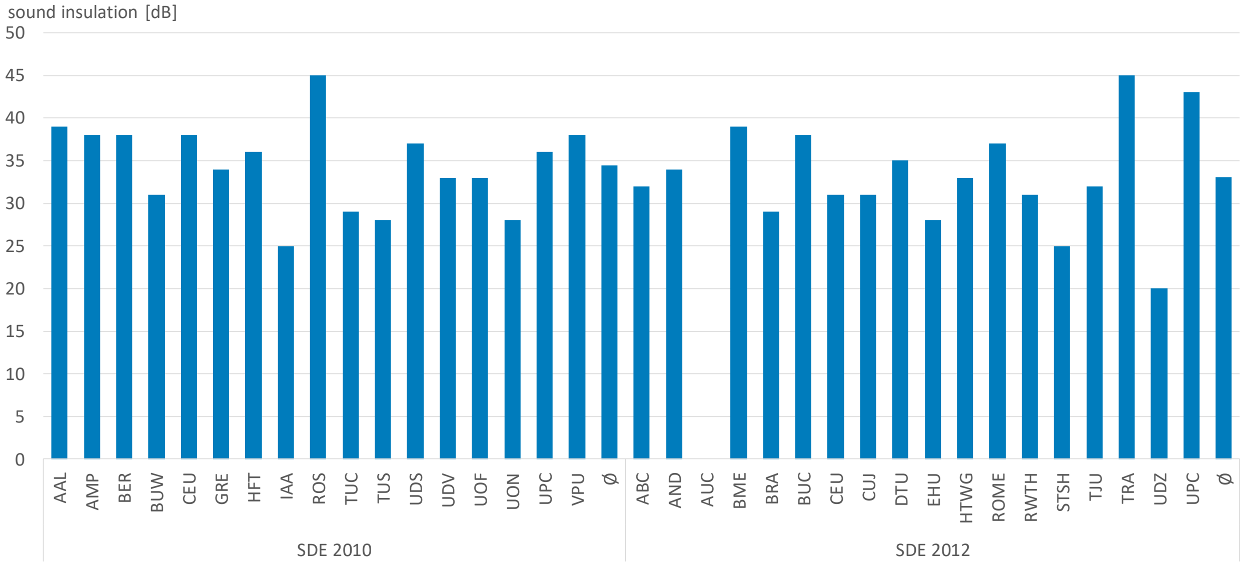

Figure 52: Comparison of the sound insulation of the facades of SDE homes tested in SDE 2010 and 2012. Source: Technical University Madrid

2.3.1 Load-Bearing Material

Wooden load-bearing structures were the preferred choice (90%) of the SDE teams (Figure 53). Only a third of the SDE teams (23) used steel as one of the main load-bearing materials. Six of these houses used steel as the only load-bearing construction. Timber and steel constructions both allow for a high degree of prefabrication. With a steel construction prefabrication of at least parts of the building is mandatory. Compared to timber, steel comes with the disadvantage that it is usually heavier. In addition, any misfits of parts cannot be resolved on site and new parts need to be ordered.

Supporting structures made of concrete were demonstrated in SDE 2014 by the Parisian Team PAR and in SDE 2019 by the Delft team (2019 DEF). The 2019 DEF team thereby demonstrated the transformation of a former office building for residential purposes and reused parts of the building's existing structure. Based on their country-specific background, in SDE10 the team from Shanghai, China (2010 TUS) used bamboo for the building's load bearing structure (Figure 54). The house is an excellent example of a house built for a European competition but with an Asian cultural background.

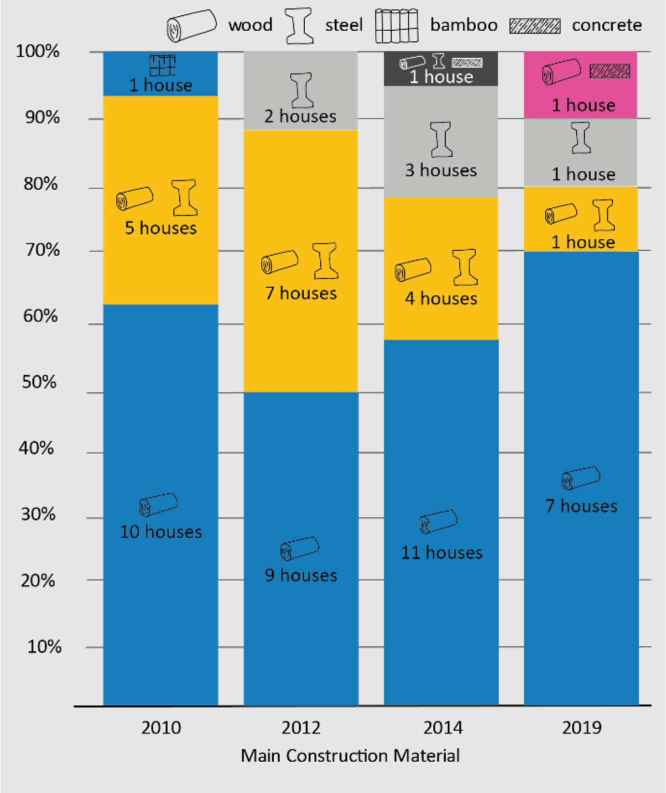

Figure 53: Representation of the utilized load-bearing materials with the distinction whether the structure was manufactured from one material or more. Source: University Wuppertal, Susanne Hendel

Figure 54: The SDE 2010 TUS house demonstrates the use of bamboo for load bearing as well as cladding. Source: SDE, Flickr [sde flickr doc]

Figure 55: Massive constructions are not common in the SDE context. Because teams only have 10 to 14 days to assemble their houses on the event site and all houses need to be transportable, constructions based on reinforced concrete are not feasible. However, the SDE 2019 focused on existing building renovations and the organizers gave all teams the unique possibility to request a building structure that would be built prior to the arrival of the teams. Only the teams DEF (MOR of the TU Delft) took advantage and requested a concrete structure. This structure is kept visible from the inside. Source: University Wuppertal, Susanne Hendel

A rare material used in the SDE is concrete. Because the houses need to be transportable, simply and speedily assembled and disassembled, stone or concrete based constructions are not feasible. However, two out of 65 SDE teams used concrete. For example, the MOR house of the 2019 Delft team has a massive concrete load-bearing construction (Figure 55). This was only possible because the necessary concrete structure was built by the SDE 2019 organizers prior to the assembly period. The DEF team prefabricated wooden parts and elements and built them on site into the existing concrete structure. Concrete constructions give the house a comfort advantage in summer due to their additional thermal inertia. In this case the background was to show the work with an existing building structure.
The timed constructions used in the SDE demonstrate highly insulated walls, floors and roofs. Due to the limited size of the building sites, teams search for wall constructions with minimized thickness without loss of living area inside the homes. Most timber frame walls realize a given U-value with less overall thickness compared to massive constructions, making them more attractive with lower U-values set by the national building codes. In real life, buildings often use the full legal plot size and homeowners are not interested in thick walls which reduce the living area. Of course, sound insulation and other properties have to be studied and considered. Sound insulation was measured at most of the SDE editions in Europe, stimulating light constructions with sufficient sound insulation.

2.3.2 Materials for thermal Insulation

As already discussed, thermal insulation of the building envelope is key issue. The materials utilized for insulation were more numerous than those for the load-bearing structures. Figure 56 provides information on the types of insulation applied. Insulation materials are classified by source in the categories for natural, mineral and synthetic materials [hillebrandt 2018, p. 86]. Natural and mineral fibers, materials such as hemp or mineral wool were favoured in the SDE. The main mineral insulation materials used were rock wool, mineral wool and foam glass. As synthetic insulation mainly expanded or extruded, polystyrene was installed. High performance vacuum insulation boards were demonstrated in various applications in SDE homes. Due to their high costs, these materials are preferably applied in situations where space is critical. Their application profits from the prefabrication of building elements or modules to prevent damage to the sensible material.

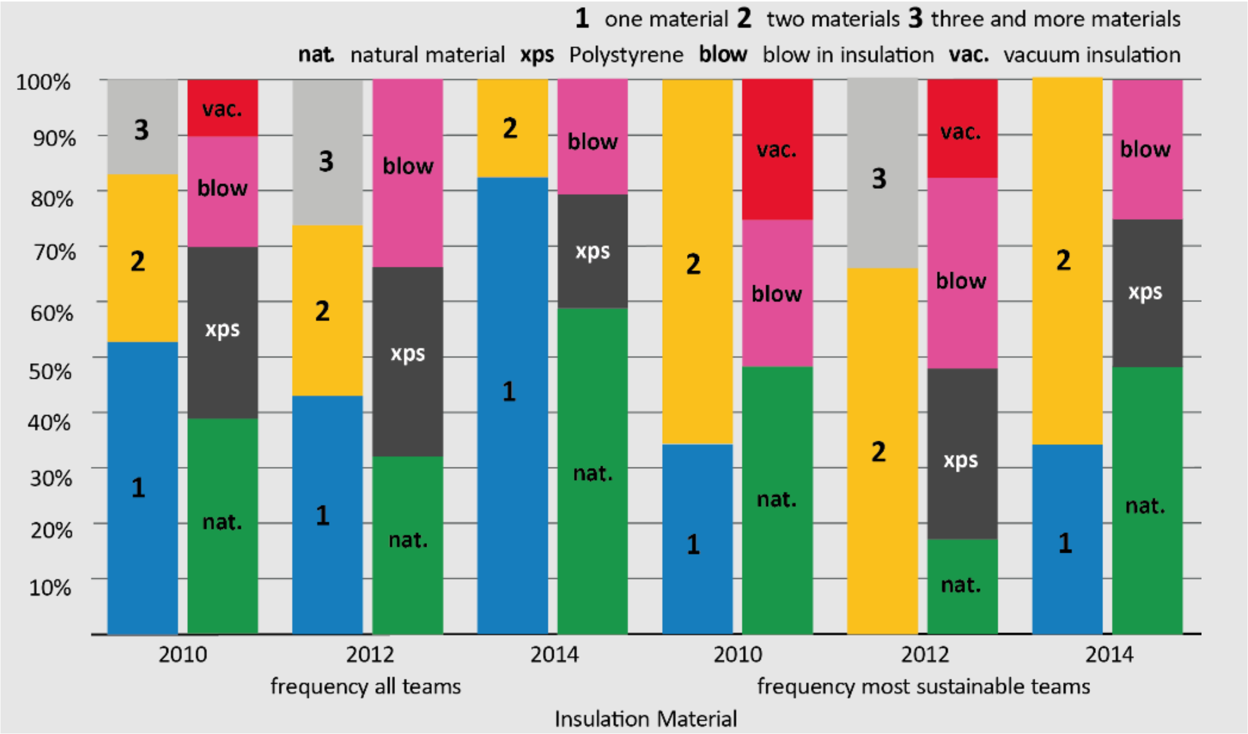

Figure 56: Representation of the insulation materials utilized. Source: University Wuppertal, Susanne Hendel

In almost all cases, the insulation material was installed within cavities with the option of being removable. This is typical for prefabricated homes but is not the case for the general housing market in Europe. Composite systems for external insulation are a typical feature of massive buildings because of their economic advantage. The circularity potential of these constructions is lower compared to the systems applied in the SDE.

Figure 57: Vacuum insulating panels visible at the 2010 UDS (Solarkit) house during assembly. Source: SDE, Flickr, Javier Alonso Huerta [sde flickr doc]

The team from Seville, Spain (2010 UDS) prefabricated building modules which were delivered to the site with vacuum insulation boards already in place. Figure 57 shows the house on day 9 of assembly at the SDE site.

Figure 58: Cork insulating boards visible at SDE 2010 during assembly. Source: SDE, Flickr, Javier Alonso Huerta [sde flickr doc]

Although natural fibre insulating materials and mineral insulating materials were most frequently used in SDE, only a few pictures of installation situations could be found. Since most of the houses were prefabricated in components, most of the insulation materials arrived at the event site already in place and cladded. An exception is the out of contest project shown in the Figure 58, which was built at the site in 2010. In this case, building modules, which were equipped with external corkboards, were brought to the site.

A detailed examination of the results of the sustainability contest shows no direct correlation between the insulation material chosen and the sustainability contest scoring. However, the life cycle footprint of materials from natural sources is significantly lower in general. This makes them particularly favourable for large insulation thicknesses: the embodied energy of a material is constant for every cm of insulation but the operational energy saving per cm decreases by thickness.

2.3.3 Surface Cladding

Exterior cladding

Surface cladding is an essential design element. It can serve the building's efficiency with additional functions. The exterior surface cladding material is always in a design dialogue with the installed solar systems as solar systems usually occupy a large part of the building envelope of SDE houses. Apart from interior design aspects, the interior cladding influences the indoor climate. Interior surfaces can serve as hygro-thermal buffers depending on their physical properties. For the evaluation, the materials for the external shell and the surface cladding in the interior are considered separately.

Figure 59: Recycled CDs as external cladding at the 2012 RWT house. Source: University Wuppertal, Karsten Voss

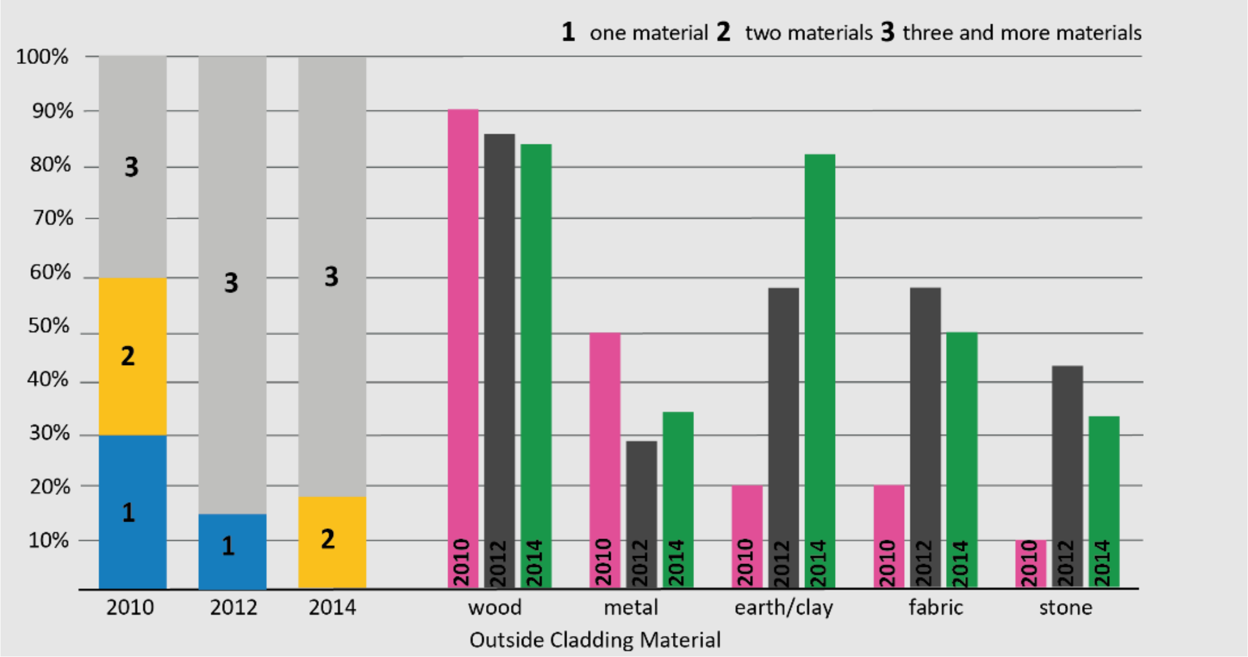

Figure 60: Materials utilized in the SDE houses for the surface cladding of the external shell of the building. Source: University Wuppertal, Susanne Hendel

About 80% of the SDE teams used wood for the façade cladding and/or the exterior elements such as terraces and pergolas. The use of wood as a cladding material on a wooden load-bearing structure was preferred.

By reviewing only, the three best teams in the discipline for construction, all 12 winning teams in the three SDE competitions have selected not only a purely wooden load-bearing construction but also wood panelling for the walls. This can be explained by the positive image of wood as a construction material. Wooden cladding gives the construction visibility and is often associated with eco design. Single material constructions are easier to recycle than other constructions. The wood panelling was supplemented on 70% of the houses by other materials. These supplementing materials were metal, stone and textiles.

Half of the SDE teams consider special climate-regulating materials or constructions such as clay or wall vegetation. Although no special experiments were undertaken to examine performance, the constructions contribute to the indoor climate conditions without active humidification or dehumidification.

Due to the sustainability contest, some teams paid special attention to the cladding materials selected as regards their sustainability. In some cases, this led to unusual concepts. For example, the SDE 2012 RWT cladded the external walls with old CDs, which they melted together to form larger panels (Figure 59). Solutions like this demonstrate a creative approach to dealing with sustainability goals in the architectural language of a project. Of course, such approaches are easier to address in temporary buildings than in the general building stock. On the other hand, prominent examples such as the Europe Building of the European Council in Brussels exist and address recycling materials for new buildings [wiki]. Examples for the large variety of cladding materials in the SDE houses are illustrated by Figure 61 to Figure 64.

Figure 61: Wooden outside cladding at the SDE 2010 HUT house. Source: SDE, Flickr, Flakes [sde flickr doc]

Figure 62: Translucent façade cladding at the SDE 2014 BAR house. Source: SDE, Flickr, Valeria Anzolin, Jason Flakes [sde flickr doc]

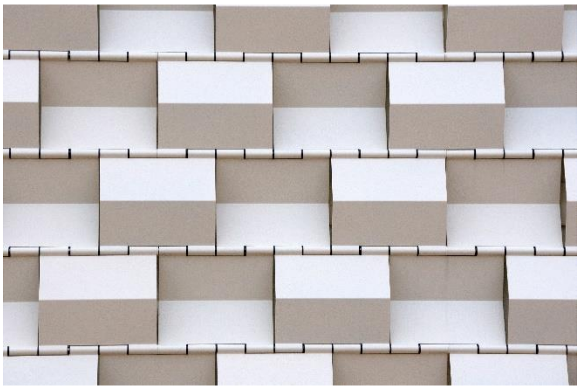

Figure 63: Metal outside cladding on the ventilated façade of the SDE 2010 ROS house. Source: SDE, Flickr [sde flickr doc]

Figure 64: Textile membrane as the outside shell of the SDE 2014 INS house. Source: SDE, Flickr, Valeria Anzolin, Jason Flakes [sde flickr doc]

Interior Cladding

With regard to interior cladding, a classification can be applied for materials with or without special properties to improve indoor thermal comfort. Materials with special properties are, for example, latent heat-storing materials (phase change materials, PCM) for temperature regulation or materials such as clay for humidity buffering. Figure 65 gives an overview of the materials applied.

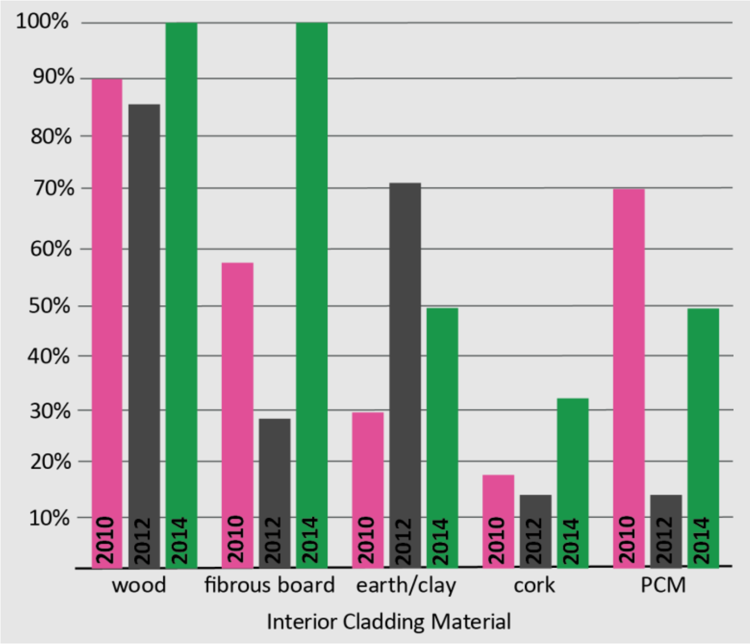

Figure 65: Distribution of materials used as interior cladding in the SDE houses. Source: University Wuppertal, Susanne Hendel

Apart from wood, which was once again the favourite material for interior cladding, and PCM to increase the thermal mass of the constructions, some teams chose clay cladding (Figure 68). Earth and clay cladding have the advantage of working as a combined hydro-thermal buffer. Over 90% of the SDE houses had wooden interior panelling or flooring (Figure 66). As with the exterior cladding, wood was supplemented in the interior spaces with at least one more material. Using bamboo as interior cladding was the direct consequence of using bamboo for all load-bearing constructions and exterior surfaces in the SDE 2010 TUS house (Figure 67).

The Figure 66 to Figure 69 show examples of SDE interior designs. The visual identity of each house has been shaped by the used materials. The surface of materials defines the interior design by bringing material patterns and construction patterns into a room. Materials can also influence the shape of a room with their specific properties such as the textile membrane roof. Some designs are definitely more experimental than those applied in the real market.

Figure 66: Wooden interior design in the SDE 2010 HUT house. Source: SDE, Flickr [sde flickr doc]

Figure 67: Bamboo interior in the SDE 2010 TUS house. Source: SDE, Flickr [sde flickr doc]

Figure 68: Interior clay walls in the SDE 2010 AMP house. Source: SDE, Flickr [sde flickr doc]

Figure 69: Interior design with membrane and wooden surface claddings in the SDE 2014 INS house. Source: SDE, Flickr, Valeria Anzolin, Jason Flakes [sde flickr doc]

2.3.4 Thermal Inertia

The disadvantage of all prefabricated, light-weight buildings in summer conditions such as the SDE final competition period is the lack of thermal inertia. Some teams add thermal mass in the form of massive floor elements. An example is given with Figure 72. In this case the placements of the floor plates reflect the positions where the sun may hit the ground. With this approach, the additional elements reach the highest effect.

An innovative solution studied in many SDE homes is the application of phase change material (PCM) as part of the interior cladding (Figure 70). Materials are chosen with a phase change temperature 1 or 2° K below the maximum temperature for the summer thermal conditions in the competition (typically 26°C). This allows the material to melt and store energy during the day with the aim of discharging it at night. Designed for summer thermal comfort, the materials are not significantly beneficial during winter as the melting temperature is too high.

PCM is a common generic term for materials such as paraffin or salt hydrates; paraffin can be micro-encapsulated and added to the plaster or gypsum boards. Ultimately, the materials do not differ visually from materials without paraffin, but the thermal storage mass can be increased to a certain extent. The upper limit of PCM content in such applications is mainly set by fire protection regulations as paraffin is flammable. Salt hydrates become part of separate constructions. Mainly bags or boards prove to be suitable. In the house MOR of the Delft team in SDE 2019, salt hydrate plates were installed in cavities in the wall constructions, as shown here by Figure 73. Usually, such PCM boards would not be visible, but the 2019 DEF team left a window in the wall construction for demonstration purposes. In the 2019 DEF house, the PCM is connected to the HVAC systems and excess heat is discharged at night by mechanical ventilation. In most SDE houses, natural or mechanical ventilation is used to discharge the PCM.

Based on the monitoring data from the SDE competitions, it is not possible to carry out a performance analysis which focuses solely on PCM.

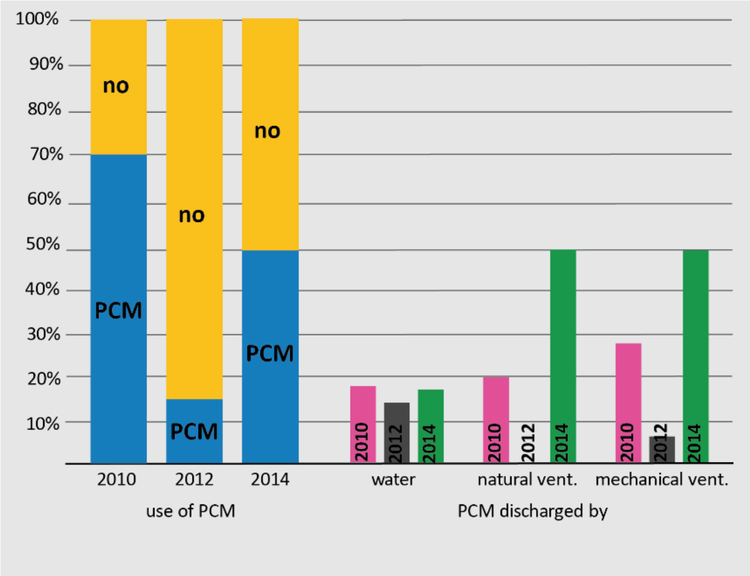

Figure 70: Overview of the PCM applications in the SDE houses. The graphic shows the number of applications as well as the type of discharging designed. Source: University Wuppertal, Susanne Hendel

An overview article on PCM use in SDUS 2005, 2007 and 2009 was published in Energy & Buildings [rodriguez-ubinas 2012].

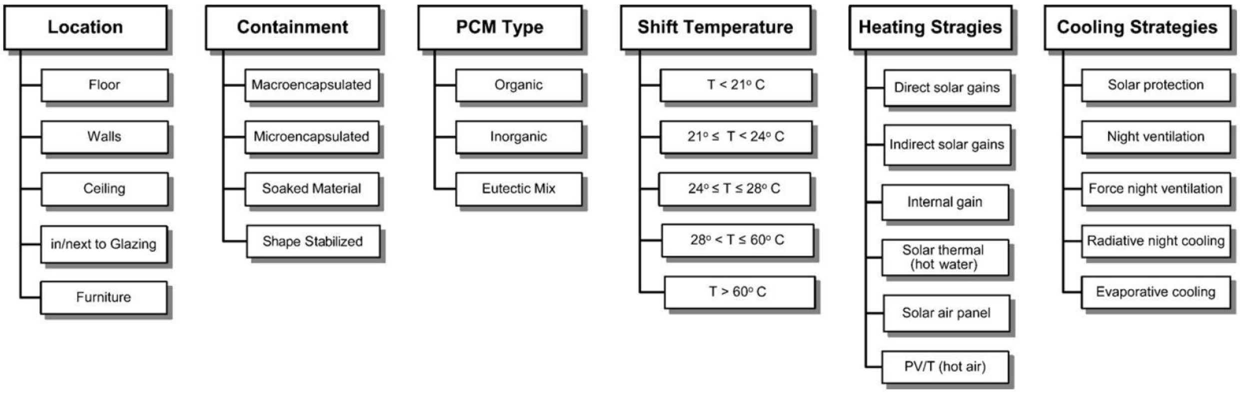

Figure 71: Overview of the factors influencing the performance of PCM applications in buildings Source: [rodriguez-ubinas 2012]

In about half of the houses, the thermal storage capacity of the construction was increased by the use of phase change materials. From the teams using PCM, barely half select a passive discharging process. The PCM is discharged by means of natural night ventilation thereby avoiding the additional electricity usage caused by fans. On the other hand, active ventilation better secures the discharging process at suitable conditions such as sufficiently low outdoor temperatures at night.

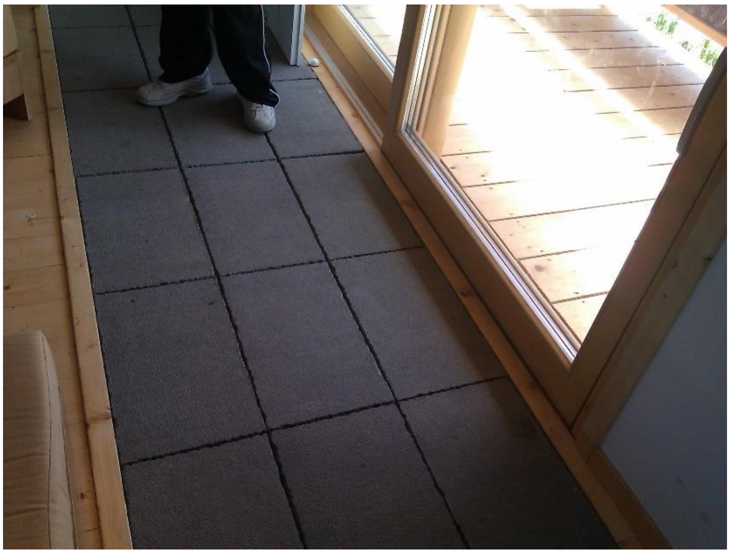

Figure 72: The PRISPA Team at SDE 2012 place thermal mass with concrete floor plates exactly in locations were the sun hits the floor. Source: University Wuppertal, Karsten Voss

Figure 73: Example for a PCM panel behind interior cladding with a woodchip board in the Team Delft home for SDE 2019. Source: University Wuppertal, Karsten Voss

2.3.5 Sustainability in Construction

Sustainability was a jury contest in all SDE competitions (Figure 74 to Figure 76). All juries decided that houses with load-bearing structures made of one material only were advantageous compared to others. Their constructions were awarded places 1 to 5 out of about 20 in both the disciplines for construction and sustainability. Constructions that used the same material for load bearing as well as cladding were considered honest designs. These constructions have a higher recycling potential.

In addition to the choice of material, the type of structural connection plays an important role in the reusability of materials, building elements or entire buildings. In particular, the possibility of assembling and disassembling most SDE houses several times gives them a unique circularity. In addition to the choice of material, the fastening and connection elements are also relevant for quick and repeated assembly, disassembly and later recycling of the materials.

The spirit of using fewer materials and creating constructions that can be reassembled or recycled is an important message taken from the SDE to building practice. Building professionals could study many SDE house designs and constructions with regard to improved circularity.

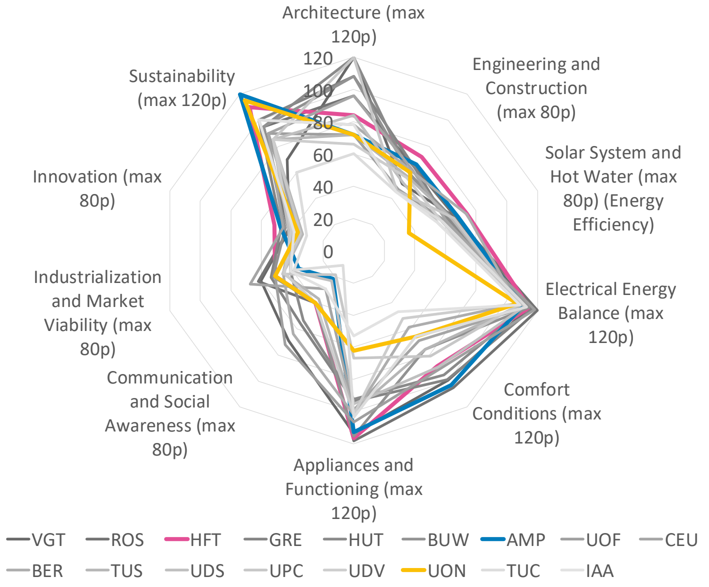

Figure 74: Overview of the scoring distribution of all contest and all teams in the SDE 2010. Teams that scored best in the Sustainability contest are coloured. Source: University Wuppertal, Susanne Hendel

1. AMP (pure material construction, prefabricated modules)

2. UON (pure material construction, prefabricated elements)

3. HFT (mixed material construction, prefabricated modules)

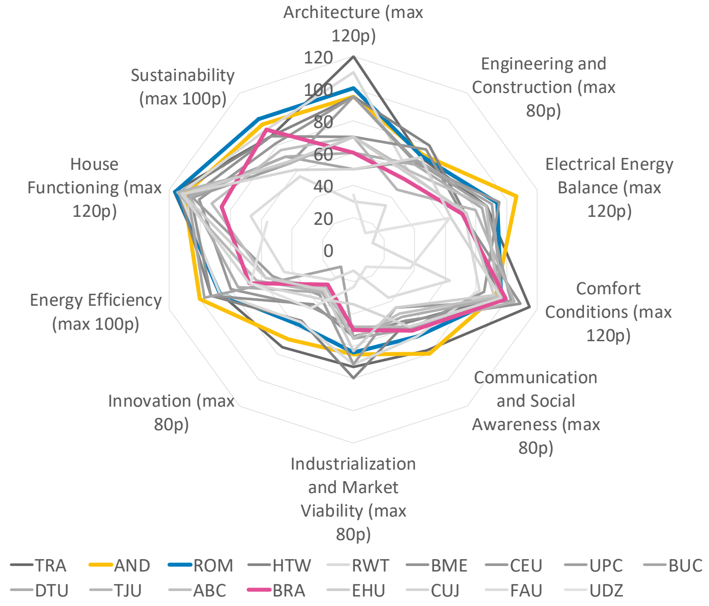

Figure 75: Overview of the scoring distribution of all contest and all teams in the SDE 2012. Teams that scored best in the Sustainability contest are coloured. Source: University Wuppertal, Susanne Hendel

1. ROM (pure material construction, prefabricated elements)

2. AND (pure material construction, prefabricated modules)

3. BRA (mixed material construction, prefabricated elements)

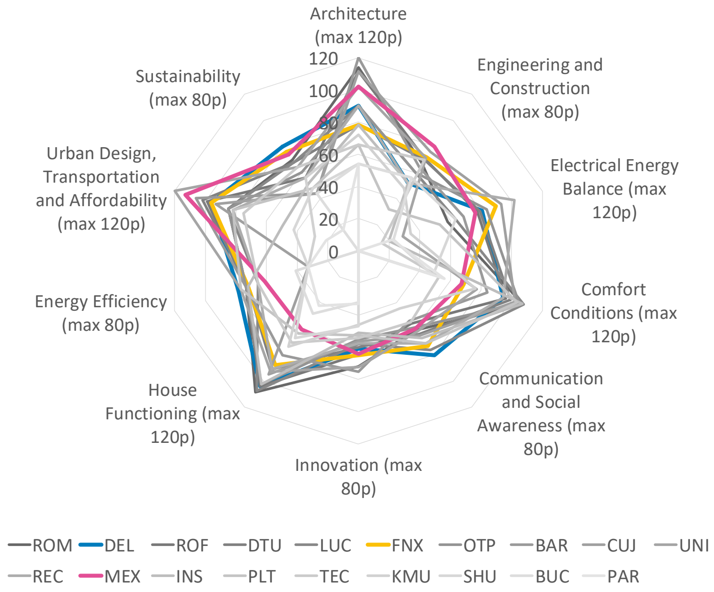

Figure 76: Overview of the scoring distribution of all contest and all teams in the SDE 2014. Teams that scored best in the Sustainability contest are coloured. Source: University Wuppertal, Susanne Hendel

1. DEL (renovation, mixed material use, prefabricated modules)

2. FNX (pure material construction, prefabricated modules)

3. MEX (pure steel construction, prefabricated modules)

2.4 Solar System Integration

As the competition is about net zero or net energy positive solar buildings, there is a unique density of solar system solutions and related innovation. Due to their size, especially in relation to the size of the building, the solar systems (Figure 77) of the SDE houses are, in many cases, prominent design features. This is especially the case with regard to PV and less for solar thermal systems. Following a systematic analysis [munari-probst 2019] different approaches are considered with respect to:

- visibility: how prominent are the solar systems in the architecture?
- materiality: is the material of the solar system different or identical to additional external cladding?
- geometry: is the solar system grating identical or different from the other external cladding?
- detailing: how are visible joints and connections solved to contribute to a convincing image?

The Figure 78 to Figure 81 illustrate these aspects with selected examples. The technological aspects of the active use of solar energy in the SDE are considered in the separate section in this report on "Energy Engineering".

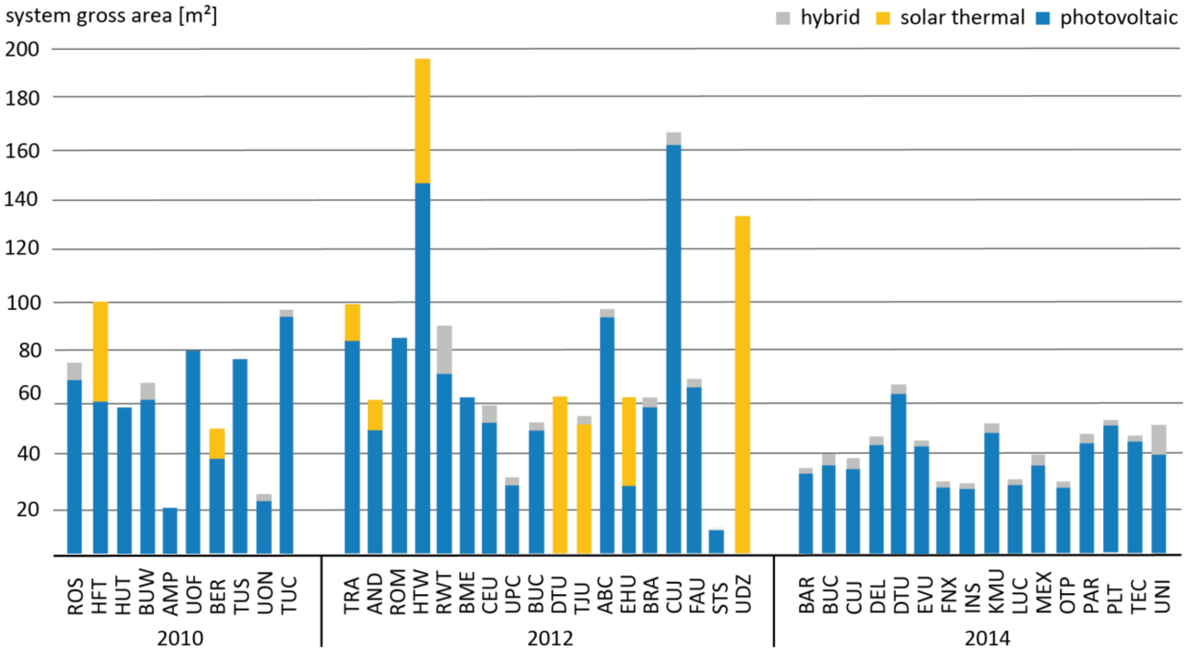

Figure 77: Size and solar system type used in the past SDE competitions. Source: University Wuppertal [voss 2016]

Apart from energy from the solar village grid, solar energy is the only source of energy available to all SDE houses. However, using energy from the grid leads to a deduction of points. All SDE houses are characterized by extensive use of solar energy. However, the houses vary significantly with regard to the visibility of the solar modules. Whereas houses such as the SDE 2012 RWT house (Figure 78) have no solar systems visible to visitors, ones such as the SDE 2010 HFT house (Figure 79) have solar modules that are the definitive design element on the building envelope.

Figure 78: On the Counter Entropy 2012 (RWT) no solar systems can be seen. Source: SDE, Flickr [sde flickr doc]

Figure 79: The SDE home+house of the Hochschule für Technik in Stuttgart (HFT) has coloured photovoltaic modules on the façade as its definitive design element Source: University Wuppertal, Karsten Voss

The perception of the SDE houses differs not only because of the visibility of the modules but also because of their interaction with the other materials used in the building envelope. When choosing their materials, some of the teams decided to visually integrate the solar modules as can be seen in the example of the SDE 2019 DEF house where solar modules were selected which have a similar appearance to façade cladding due to their matt surface. This type of façade cladding is standard on high-rise buildings. The SDE 2019 DEF house has no optical break between the façade cladding and the solar systems (Figure 80). The SDE 2012 Ecolar (HTW) house deliberately foregrounded the contrast between the black solar modules and the wooden façade (Figure 81). In this case, the break in materials and colours used to lead a coherent design with the solar modules supplementing the formal language of the building.

Figure 80: The MOR house (DEF) at SDE 2019 presents a module for high-rise renovation. The façade cladding comprises matt photovoltaic modules which match the colour of the windows by a ceramic ink on the surface. Source: TU Delft, Project Drawings

Figure 81: On the SDE 2012 Ecolar (HTW) house, the solar modules are in direct contrast to the wooden façade. Source: University Wuppertal, Karsten Voss

The geometry of solar modules and their arrangement determines whether the systems are perceived as an added or integral part of the building. In the examples of both the SDE 2010 SML house (CEU) and SDE 2012 Unizar (UDZ) house, solar modules were installed on the façade to contrast with the other colours and materials used. The geometry of the CEU house modules complements the façade and they appear integrated (Figure 82). In contrast, the UDZ house modules appear to be added on due to their hexagonal form; they contrast with the rest of the building and the rest of the façade which is smooth and white (Figure 83).

Figure 82: One example of the integrated geometry of solar modules on the facade of the SDE 2010 SML house (CEU). Source: University Wuppertal, Karsten Voss

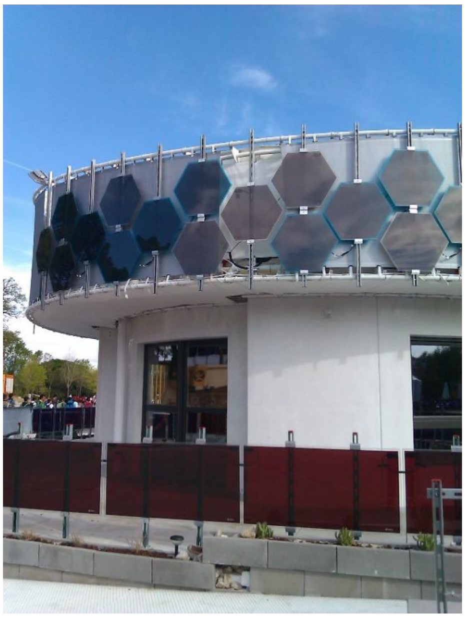

Figure 83: On the SDE 2012 Unizar house (UDZ), solar modules were added to the façade. The hexagonal form of the modules emphasizes the complementary design approach. Source: University Wuppertal, Karsten Voss

Apart from the positioning and design of solar modules, the load-bearing construction of the systems also determines the overall appearance which is also demonstrated by the range of solutions displayed at the SDE. Displaying the substructure can also be used as a design element which was the case in the SDE 2012 FAU house (Figure 84). This construction optically dominates the underlying building.
A different approach was taken by the SDE 2012 ROM team. The solar modules were extended beyond the roof onto the façade as was the case on the FAU house; however, on the SDE 2012 ROM house a lean and non-dominant substructure was chosen (Figure 85).

Figure 84: Solar system built over a dominant substructure on the SDE 2012 CEM NEM house (FAU). Source: University Wuppertal: Karsten Voss

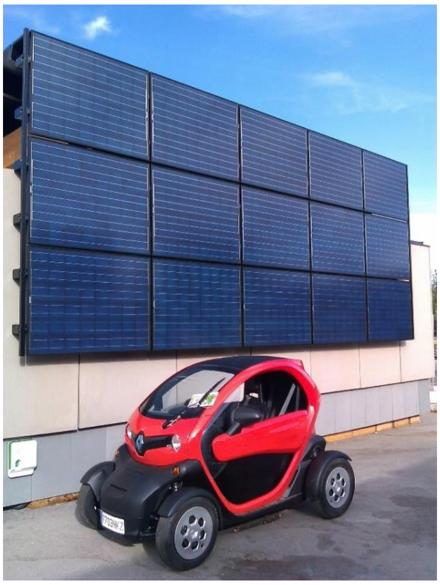

Figure 85: Solar system on a non-dominant substructure extending beyond the roof and over part of the façade of the SDE 2012 Med in Italy house (ROM). Source: University Wuppertal Karsten Voss

The SDE houses are models for solar energy use; more surface area was given over to photovoltaic or solar thermal elements than is usually the case in building practice. It was important to integrate these elements in order to achieve a good score in the architecture discipline. Therefore, only a few teams decided to add solar technologies onto their houses; however, this is currently the most common practice in the building industry. The integration of solar modules should always be seen within the context of the overall design.

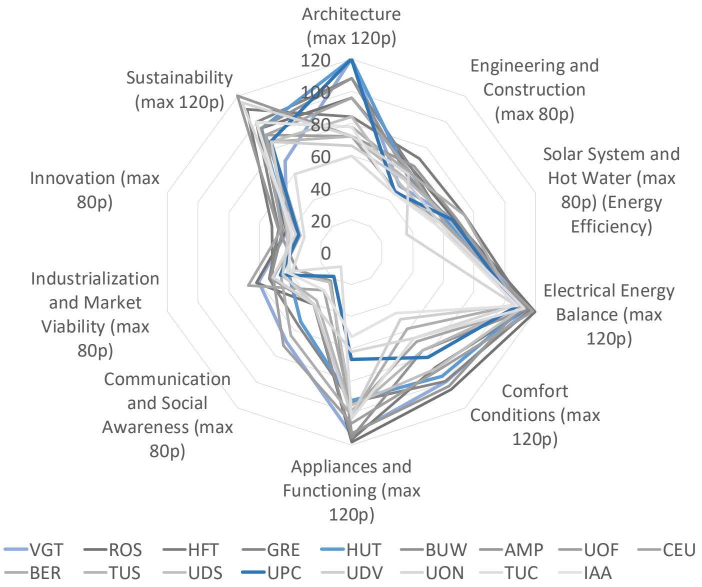

Figure 86: Overview of the scoring of all contests and all teams in the SDE 2010. Teams that scored best in the architecture contest are highlighted in blue. Source: University Wuppertal, Susanne Hendel

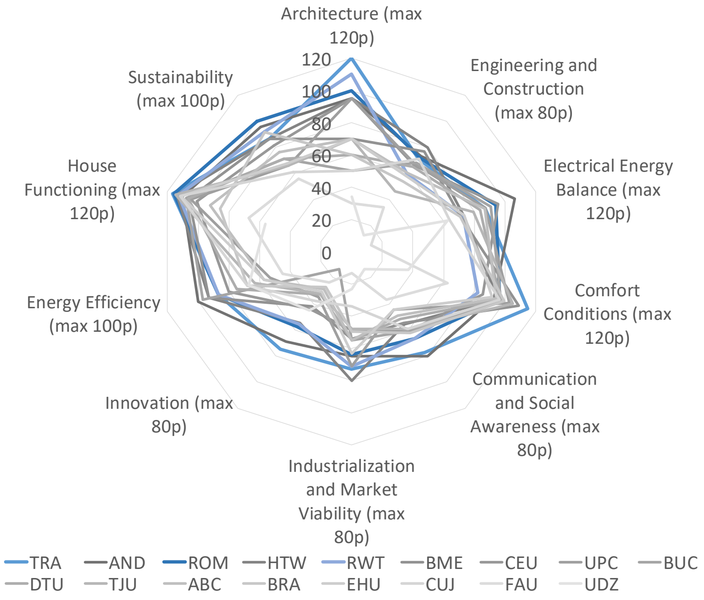

Figure 87: Overview of the scoring distribution of all contests and all teams in the SDE 2012. Teams that scored best in the architecture contest are highlighted in blue. Source: University Wuppertal, Susanne Hendel

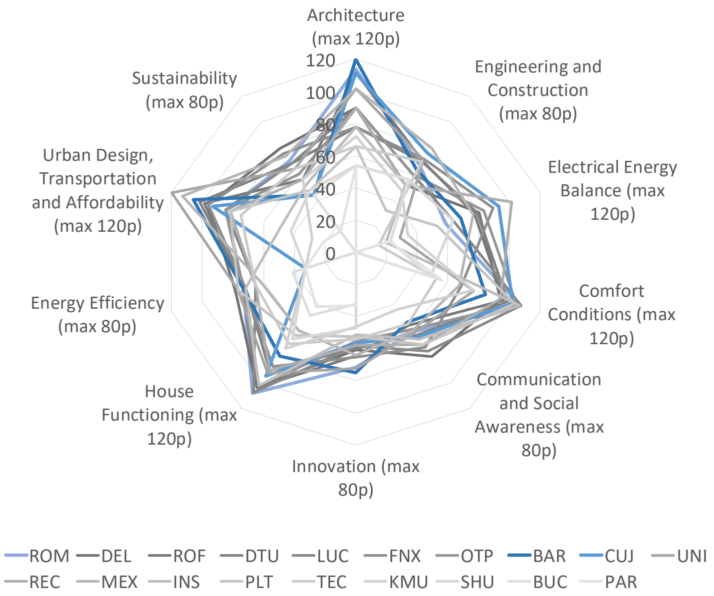

Figure 88: Overview of the scoring distribution of all contests and all teams in the SDE 2014. Teams that scored best in the architecture contest are highlighted in blue. Source: University Wuppertal, Susanne Hendel

In each of the three teams ranked highest in the architecture contest there are no overlaps with the teams in the energy efficiency or sustainability contests.

All of the three top teams integrated solar modules. However, the designs differ with regard to whether the solar modules are a visible or dominant part of the design or if these are barely or not at all visible to the visitor, as regards the colour and geometric design chosen and how the substructure design was executed. All houses were awarded prizes in the architecture discipline and demonstrate different approaches to integrating solar energy technologies; therefore, they demonstrate options which can also be adopted by the building industry.

Some of the SDE houses differ fundamentally in their design from European building practice. This is primarily due to the lack of a site context in the competition and the building tasks which were often freely chosen. Most of the solutions presented at the SDE cannot be adopted as an overall concept by the building practice. However, the solutions presented for the integration of solar systems are transferable.

2.5 Conclusion

The SDE houses show a variety of approaches for future living and building and experience of them can bring impulses to European building practice. Although the SDE houses differ significantly from standard European buildings, they can serve as role models for future buildings.

Compared with standard European constructions, the SDE houses are significantly smaller, have a simple cubature, but an unfavourable form factor and a lack of thermal inertia; they also need to be transportable and lack an urban context. However, for each SD between 10 and 20 of these special houses are built on the event site. All of them are comparable in size, usage and location.

The large number of highly comparable, extensively documented and tested houses offered by the SD is unique. This enables knowledge to be gained about building solutions, their performance and also provides inspiration for their potential implementation in building practice. The differences between SDE houses and standard buildings plus the high expectations they need to fulfil in the competitions can be interpreted as a framework that is more difficult than the framework standard buildings in Europe face; this makes the results even more interesting. The SDE houses present solutions for interior comfort and to construction challenges.

To secure a comfortable indoor climate without using an extensive amount of energy, the SDE houses applied passive design strategies. The strategies evaluated here are shading systems, buffer zones, passive ventilation and the placement of vegetation and wetlands.

To deal with the challenge of building a transportable and highly efficient house with well-rated architecture, the SDE teams paid special attention to their constructions and the materials used. The degree of prefabrication and choice of load-bearing and cladding material had a significant influence on the success of assembly and disassembly of the houses as well as on their performance during the competition.

Based on the existing documentation, the houses can be best evaluated on the basis of their competition scores. In particular, with regard to the contests “Energy Efficiency”, “Sustainability” and “Architecture”, the houses were judged by an international expert jury. These contest scores were used to evaluate the passive building solutions implemented in the SDE houses.

This evaluation showed that buildings with an extensive use of passive technologies are more likely to secure a comfortable and stable interior climate without the need of energy and active technologies. Passive technologies contribute to the enhanced efficiency of the buildings. The effectiveness of individual passive measures cannot be determined within the scope of the SDE. However, in all SDE houses passive measures have been implemented to maintain interior comfort, especially since the introduction of the so-called passive period. The example of the temperature measurements of the SDE 2012 houses could show that all of these houses were able to maintain a comfortable interior climate despite the challenging conditions they faced.

Passive technologies can be either dominant or integrated design elements. For example, solar chimneys or roof elements for a venturi-effect ventilation may be very visible on a building. Moreover, both elements are rather uncommon in European building practice and are hard to imagine in an inner-city environment. Nevertheless, both solutions could become more relevant in Europe, especially if periods of increasingly lengthy warm temperatures in the summer months are taken into consideration.

Other passive elements such as the ventilated façade, buffer zones integrated into the floor plan and shading elements are already an integral part of building practice. However, the SDE provides a large number of at times more experimental and unusual examples which could inspire building practice, which is in part rigid, to adopt new and more efficient ways of building.

For the successful dissemination of passive solutions, future competitions should communicate their performance. Until now, only point scores and measurements have been published. The point scores of the jury disciplines do not per se provide evidence of what was considered as particularly constructive and of what could be of particular interest to the building profession and an interested public. The performance results are difficult for an interested public to interpret and are even difficult for experts to fully comprehend without any additional documentation of the surrounding conditions.

The members of the jury agreed that honest constructions with just one material are more sustainable than structures which use different materials for the load-bearing structure, insulation and cladding.

Constructions with material purity have an increased recycling potential; moreover, it opens up new possibilities for building practice if the houses can be transported and easily converted. The SDE houses are all designed for rapid assembly, disassembly and reassembly. A high level of prefabrication has proven to be advantageous. The prefabrication of buildings is already becoming more common in Europe and has a growing market share. In this respect, the SDE provides new innovative examples and new impulses.

SDE houses provide examples for the integration of elements for solar energy use into the design of the building. In contrast to photovoltaic or solar thermal elements which are usually added subsequently to a building, the SDE houses demonstrate a use of solar energy which has been conceived of as part of the design. The SDE shows that the use of solar energy can be either a dominant part of the building envelope or may not be visible on the building at all. A transfer of SDE concepts to building practice can be of benefit to building practice, in particular with regard to the growing need for surfaces for solar energy use.

The SDE buildings are compact demonstrations of the possibilities for maximizing a building's energy efficiency, sustainability in combination with an ambitious design. Ideas and innovations especially with regard to construction and consequent design could and should affect building practice.

3. Review Part II - Energy Engineering[15]

3.1 The Competition Framework

3.1.1 Regulations

All competitions to date related to "all-electric" homes. Apart from electricity, the only option alongside solar power is ambient air as a heat source or heat sink. Ground and groundwater heat or cold on the site cannot be included in the concept. The use of fossil fuels, biomass, biogas and hydrogen on the site is not permitted. This is primarily on the grounds of infrastructure feasibility and financing for temporary (event) structures and subsequent use of the site in question. Based on a central event concept, all houses are built on the same site. It is also designed to allow a fair comparison of the various solutions. In public relations, however, care must be taken to ensure that all-electric homes are not presented in a one-sided way as the only sustainable option for the future, as urban energy solutions in particular may take other approaches, namely district heating and cooling. The idea of a heating and cooling network for the SDE 2019 buildings was ultimately not pursued following initial planning. An urban setting was also the context for that initial idea.

The scope for the energy concepts is thus centred on supplementing a largely solar energy supply with air-coupled heat pumps or refrigeration systems. In the light of the growing use of renewable energies in the electricity grids of many European countries, the focus on electricity as an energy source reflects a current trend.

As organisers seek to stage a public event with as great an attendance as possible, all competitions to date have been held in the warm and sunny months of the year. This means that the demand for heating is usually low during the competition period, and there has been - in line with the location - a greater (Dubai) or lower demand for cooling (Madrid, Versailles, Szentendre). Figure 89 shows the heating and cooling hours calculated for a model building from SDE 2010 in realistic conditions of use such as ventilation, internal heat sources and operation of the shading systems. The number of hours per year in which the room temperature is within the comfort range of 21°C to 25°C without heating and cooling operation was calculated (named “neutral hours”). Hours above 25°C were cumulated and defined as cooling hours, and hours below 21°C were cumulated and defined as heating hours. As a result of the moderate climate during the planned competition period in late summer, the heating and cooling systems will not be in operation at all at in SDE 2021 in Wuppertal, Germany. In all European competitions, however, the houses must provide simulation calculations to proof the year-round suitability of the energy concepts as part of the requirements. An example of this is shown in Figure 91. This requirement also helps to ensure the usability of the houses after the actual competition phase. For the most part, subsequent use has been in the country of the given team and therefore in the climatic conditions of that country. Evidence has therefore generally been provided for both the climate of the competition host country and of the home country of each team.

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[15] Authors: Karsten Voss, Susanne Hendel, Moritz Stark, Andrea Balcerzak, University Wuppertal, funded by EC contract ENER/C/2016-502/SER/SI2.763962

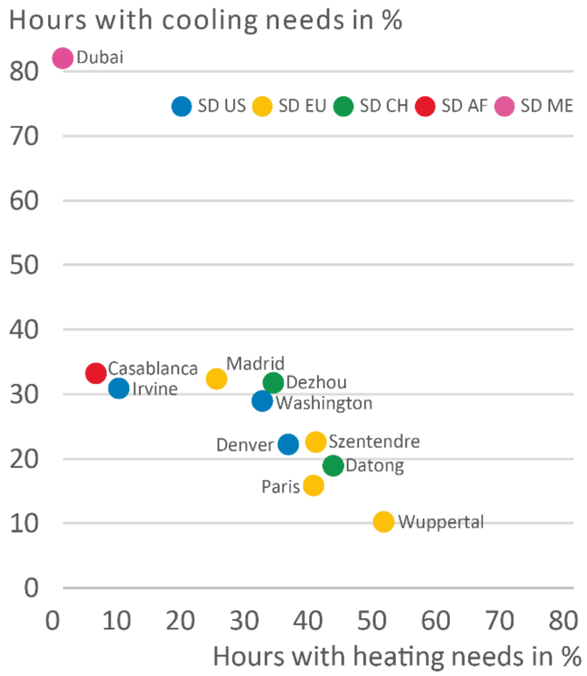


Figure 89: Annual evaluation of free-floating temperatures at all event locations. The results are broken down by heating demand hours and cooling demand hours. Neutral hours are the difference between 100% and the sum of the heating and cooling hours. Neutral hours describe the state where the indoor temperature is in the comfort range without heating and cooling (21°C – 25°C). Source: S. Hendel, University Wuppertal

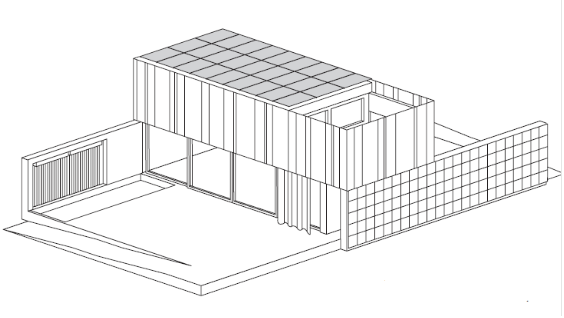


Figure 90: Illustration of the Wuppertal house at SD EU 2010 [detail 2011]. This house was used as an example to simulate the indoor climate at all event locations. Source: S. Hendel, University Wuppertal

Conditioned floor area: 49 m2; clear room height: 4.8 m; window-to-wall surface ratio: 25 %. Average thermal transmittance of opaque surfaces: 0.1 W/(m²K); average window thermal transmittance: 0.8 W/(m²K); air tightness (n50): 0.6 1/h; exterior sunscreen with shading factor: 0.2; sunscreen active above 200 W/m² incident radiation; ventilation with heat recovery with 85% efficiency and overheat protection through increased window ventilation, activates when the indoor temperature is higher than 22°C

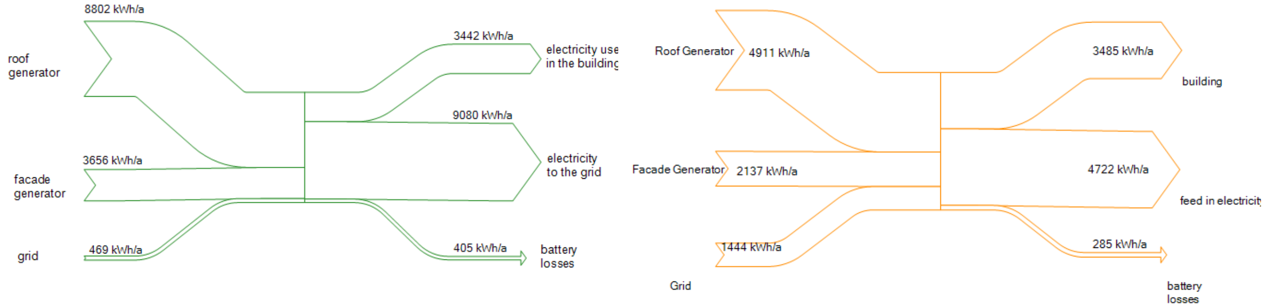
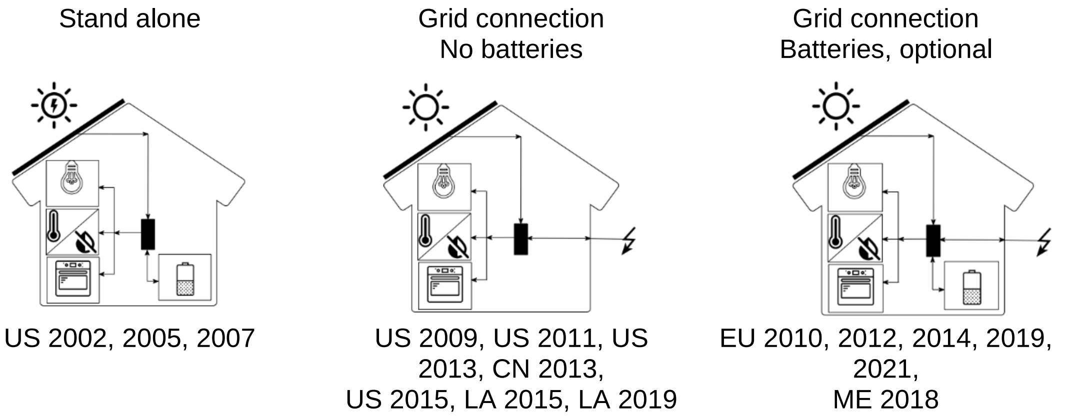


Figure 91: Energy flow diagrams (Sankey diagrams) for the annual energy performance of the house illustrated with Fig. 2.1b for Madrid (2010 competition conditions, left-hand diagram) and Wuppertal (standard conditions, right-hand diagram). Source: University Wuppertal

The first SDE 2010 in Madrid has one important focus on stimulating teams to maximize PV power installations on the building roofs and facades. This creates a large variety of building integrated solar systems. To increase the practical relevance of the small buildings including the overall building costs, more recent competitions have lowered the limits for photovoltaic system peak power or the maximum storage capacity of batteries. This is designed to maintain and even stimulate the high challenges regarding building energy efficiency for all teams. In view of the large enveloping surface per living space compared to conventional buildings (refer to Report on Building Design & Construction), large solar power systems are otherwise able to compensate even for high consumption by less efficient buildings. This is particularly true for competitions in sunny locations or at the height of summer. The maximum photovoltaic system power was limited to 15 kW_p at the very first SDE in 2010. This limit was subsequently reduced to 10 kW_p (2012) and then 5 kW_p (2014/19). The current rules for SDE 2021 set out a further reduction to 3 kW_P. The reason for this is the standard practice set for multi-family dwellings: the larger number of storeys means even less enveloping surface is available per living space in practice, in particular roof surface. In some cases, upper limits were also set for the costs of the solar technology used and evidence of market availability was required. Both these requirements reflect the tension between innovation and practical relevance. As the SDE houses are connected to the public grid, all standard certificates of conformity must have been obtained, in particular for the inverters, so that a negative impact on the grid can be ruled out.

A number of competitions have been held to date in which the use of batteries was permitted. At the first three competitions in the USA, batteries were a technical necessity because there was no grid connection. The requirements specified independent operation for the duration of the competition only. There were no requirements for year-round independent operation, which would indeed not be technically feasible even with batteries. With the introduction of grid-connected operation, the focus has changed from self-sufficient buildings to nearly zero, net zero or energy plus buildings [sartori 2011] [voss 2011]; calculations showing the annual energy balances must now also be provided. Batteries are used for the optimised adjustment of generation and consumption at SDE 2012/14/19 and at SDE 2021 also for flexible building-grid interaction. In a step similar to that for photovoltaic power, maximum storage capacities were first introduced in the European competitions. The limit for 2014 and 2019 was a nominal capacity of 6 kWh; this has been reduced to 2.5 kWh for SDE 2021. This type of specification has a major influence on the building design, the technology used and the overall building energy concepts.

To ensure the functionality of the buildings, and electrical loads as well as air conditioning during the competition, practical specifications for the operation of household appliances and consumer electronics apply in all competitions. Specific activities at given times such as laundry, running hot water and cooking, the entertainment of guests in the evening and, in some cases in the US and in Dubai, the operation of electrically powered vehicles, have also been included in the requirements. SDE 2021 will include mobility on the level of urban cargo bikes in the energy discipline.



Stand alone

Grid connection
No batteries

Grid connection
Batteries, optional

US 2002, 2005, 2007

US 2009, US 2011, US 2013, CN 2013,
US 2015, LA 2015, LA 2019

EU 2010, 2012, 2014, 2019, 2021,
ME 2018

Figure 92: Electric grid availability and battery utilisation in SD competitions, Source: S. Hendel, University Wuppertal

3.1.2 Energy-related Disciplines and Monitoring

Each SD competition evaluates the houses in 10 different disciplines. The names, rules and points for those disciplines shape the profile of each competition. Points are awarded mainly by juries, but also on the basis of measurements. The evaluation of the energy balance is always one of the core areas and, like the function of the houses and the indoor climate, is based on measurements.

Different intervals for monitoring have been applied at the different SDE competitions. For example, the data for SDE 2010 and 2014 are available in 1-minute intervals. Data at SDE 2012, on the other hand, were only recorded in 15-minute intervals. All these measurements have been compiled and processed for the knowledge platform in such a way as to allow their use in future (https://building-competition.org/). The organisers have not made available the data from SDE 2019 at the time of producing this report. Evaluation of measurements has always primarily served the ongoing evaluation of the houses in a competition in comparison to each other (scoring). The results reflect the given climatic conditions and competition rules for the operation of the houses. Comparisons between competitions are therefore only of limited use. Scientific or research use has not been the focus to date and would only be possible to a very limited extent. For SDE 2021, modifications to the regulations that should make this easier have already been planned.

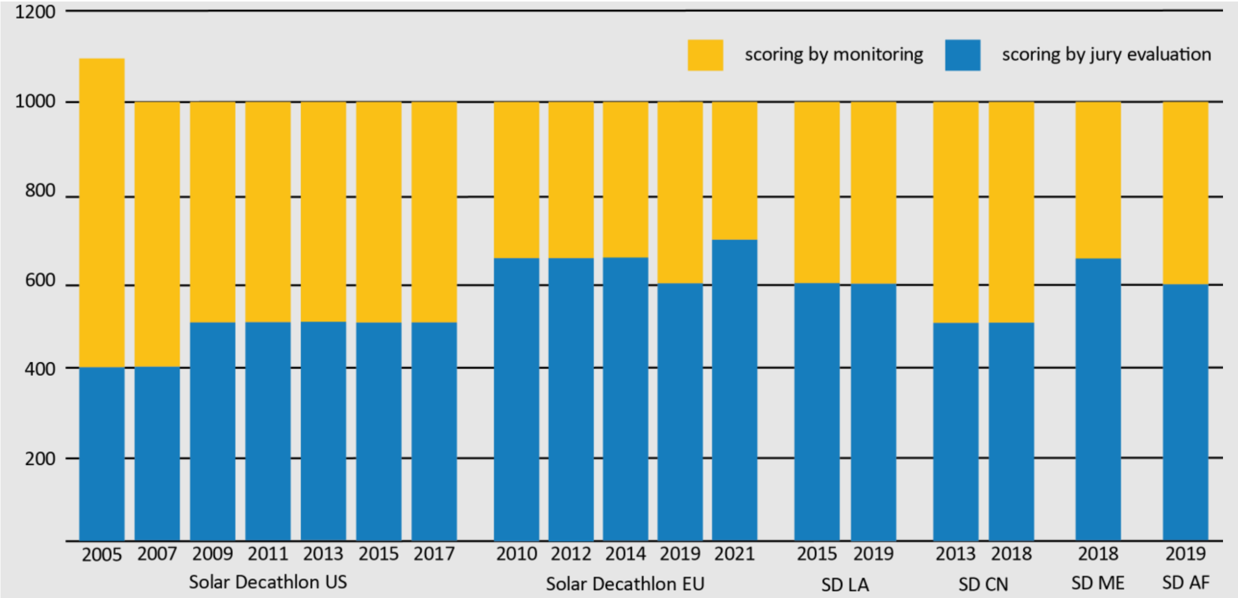


Figure 93: Breakdown of points (maximum scores) at SD competitions. Between 36% and 64% of the total points are awarded by juries. Overall, the proportion of the score awarded by the jury in SDE is higher than in SD, SD LA, SD CN and SD AF. SD ME scoring is based on SDE 2014 experience. Please note that the competition in the US 2005 used a higher total number of points with 200 instead of typically 100 for architecture. Source: S. Hendel, University Wuppertal

3.2 Active Solar Energy Utilization

3.2.1 Solar Power

Photovoltaic systems are a mandatory component of all energy concepts and occupy large areas of the SD houses. Table 6 lists the characteristics of the systems installed at SDE. Technical characteristics include cell type, system size and rated output. Most teams opt primarily for modules with crystalline silicon-based solar cells as these offer a higher output. This reflects the current market situation globally. Monocrystalline cells are preferred because of their higher efficiency. That efficiency advantage is even greater when compared to thin-film cells [county 2020-1]. A significant limitation on maximum system power has led to an increase in the variety of cell types used, as the aim is no longer simply to achieve maximum yield from a given area. Technical progress in thin-film cells, above all for the building integration market, is also contributing to greater interest in this field (BIPV: building-integrated photovoltaics). Despite the limitation on power, photovoltaic systems remain a key design element of most SDE houses; see report on “Building Design and Construction”. The wide-ranging use of modules is evident in the varied designs [cronemberger 2014].

Despite their small size, there are houses with photovoltaic systems covering almost 100 m^2 (SDE 2010: HFT, SDE 2012: EHU), which is about twice the conditioned floor space. The average system size was 7 kW_p per 50 m^2 floor space equal to 140 W/m^2. The ratio of installed capacity to floor space decreased significantly in the competitions from 2010 to 2014 as a result of changes in the rules (Figure 94, Figure 95, Table 7): Larger floor spaces were permitted and the maximum power was lowered in 2014. Ratios are thus getting closer to those in systems in standard market buildings that meet the requirements of net zero or energy plus buildings. Accompanying research has found average values of just under 70 W/m^2 for single-family energy plus dwellings in Germany (Effizienzhaus Plus) [bmi 2018]. The process thus promotes the development of buildings that are genuinely relevant for building practice.

The size, orientation and angle of systems on the individual buildings, together with the quality of installation, determine the electricity yield during the competition period. Quality of installation relates to structural aspects such as module ventilation and shading, and to electro technical aspects such as electrical adjustment between the modules and inverters. Figure 95 gives the example of the results for SDE 2010. As climatic conditions differ between the different competition locations, a comparison across competitions is not useful. Solar radiation on the systems has to date not been measured. Conclusions on the quality of system design and installation (performance ratio) therefore cannot be drawn. SDE 2021 is introducing such measurement for the first time.

Table 6: Features of photovoltaic systems on SDE buildings. The completeness of the data reflects the available documents for the individual buildings. Source: University Wuppertal

CFA: conditioned floor area, Mono: monocrystalline silicon cells, Multi: multi crystalline silicon cells, PVT: photovoltaic thermal hybrid solar collectors, CPVT: concentrating photovoltaic thermal solar collectors, CIGS: second generation of thin-film modules, BIPV: building-integrated photovoltaics. The abbreviations of the team names are based on those used on the building competition knowledge platform

Edition	Team	Cell type	System size m^2	Nominal power kW_p	Building conditioned floor area m_{CFA}^2	Specific power W_p/m^2_{CFA}	Additional function
2010	ROS	mono	70	12.6	55	229.1	Night sky radiation cooling
	TUC	mono, multi		8.4	44	190.9	PVT, shading
	BER	mono	42	5.7	48	159.5	Night sky radiation cooling, shading
	VGT			8.8	52.8	166.7	bifacial
	UDV			9	46.4	194	
	HFT	mono, multi	100.2	12	52.1	172.7	Coloured PV, PVT, night sky cooling
	UON	multi	24	2.8	72	38.2	
	AMP	mono	16	3.2	46	68.5	
	HUT	mono	59	9.0	42.4	212.3	
	IAA	mono	70	8.5	57.4	148.8	
	BUW	mono + multi		73	10.2	48.6	207.8
	UPC	multi		4.2	42	100.0	
	UDS	mono		9.6	51.7	185.7	
	TUS	mono		10	42	238.1	PVT, shading
	GRE	mono		13.8	44.7	308.7	PVT, shading
	UOF		80	14.6	46	317.4	CIGS
	CEU			10.1	50.8	198.8	
	average		*59.4*	*9.0*	*49.5*	*184.5*	

Edition	Team	Cell type	System size m^2	Nominal power kW$_p$	Building conditioned floor area m$_{CFA}^2$	Specific power W$_p$/m$^2_{CFA}$	Additional function
2012	DTU		70	9.2	59	155.9	BIPVT
	TJU		56.6	8.8	61.6	142.2	
	UPC	mono	30.0	4.3	45.5	94.9	
	CUJ	thin film	160	11.4	54.4	208.6	
	CEU	thin film, multi	51.6	7.2	56.6	126.3	
	ABC	multi	32	6.2	69.4	89.3	CPVT, night sky radiation cooling
	FAU	multi	67.6	9.2	49.2	187.8	
	RWT	thin film	77.2	6.8	61.8	109.2	Night sky radiation cooling
	AND	mono	69.3	11.3	69.6	162.6	PVT
	BRA	mono	66.6	11.0	55.6	198.6	CPVT
	BME	mono, thin film	47.5	9.0	45	200.7	CPVT, night sky radiation cooling
	BUC	mono	55	8.0	77.6	103.1	
	ROM	multi	74.7	11.8	55.5	213.3	CPVT
	STS			3.5	58.23		CPVT
	HTW	multi	35.8	1.2	67.6	17.8	CPVT, night sky radiation cooling
	UDZ	thin film		1.0	62.4	16.0	
	TRA	mono	13	2.0	68.8	29.1	PVT
	EHU	mono	91.2	12.0	49.1	244.1	CPVT
	average			*7.4*	*58.3*	*131.1*	
2014	ROM	mono	25	5.0	55.5	91.0	
	DEL	mono	44	4.9	85	57.6	
	ROF	thin film	15	4.7	55.4	84.8	Shading
	LUC	mono	14	4.7	73.3	64.1	
	FNX	multi	25	3.9	52.9	73.7	
	OTP	mono	15	4.9	110	44.5	
	DTU	mono	66	4.9	59.0	83.1	
	REC	mono		4.9	104	47.1	
	BAR	mono	29	4.5	51.7	87.0	
	CUJ	mono	30.6	4.7	75.7	62.1	
	UNI	multi	32.7	5.0	71.3	70.1	
	PAR	thin film	40	3.2	52	61.5	Roof shading, luminescent solar concentrator
	INS	thin film	23	5	76.7	65.1	Membrane-integrated PV
	BUC	multi	33.3	5	96.7	51.7	
	KMU	mono + thin film	45,2	5	112	44,6	partly triple junction amorphous SI
	MEX	mono	33.7	4.9	52.6	93.1	
	PLT	thin film CIS	49.6	4.8	61.7	77.8	
	SHU	mono	27.1	4.9	59.0	83.1	
	TEC	multi	26.0	4.0	55.5	72.1	
	average		*31.1*	*4.7*	*78*	*66,7*	

Edition	Team	Cell type	System size m^2	Nominal power kW$_p$	Building conditioned floor area m$_{CFA}^2$	Specific power W$_p$/m$^2_{CFA}$	Additional function
2019	BUD			5	70	71.4	
	DEF	mono		5	51	98.0	
	GUB	hybrid	29.8	5	69.19	72.3	PVT
	KMU	hetereo-junction	25.11	4.875	62.53	78.0	
	MIH	mono		5			
	PLF	poly	13.4	2.24	120	18.7	
	SEV		36	4.8	80	60.0	
	TUB	mono	46.76	4.97	65	76.5	
	UPC	poly	22.92	3.3	108.2	30.5	
	VAL	mono	30.53	5	54.2	92.3	
	average			*4.5*	*75.9*	*66.4*	

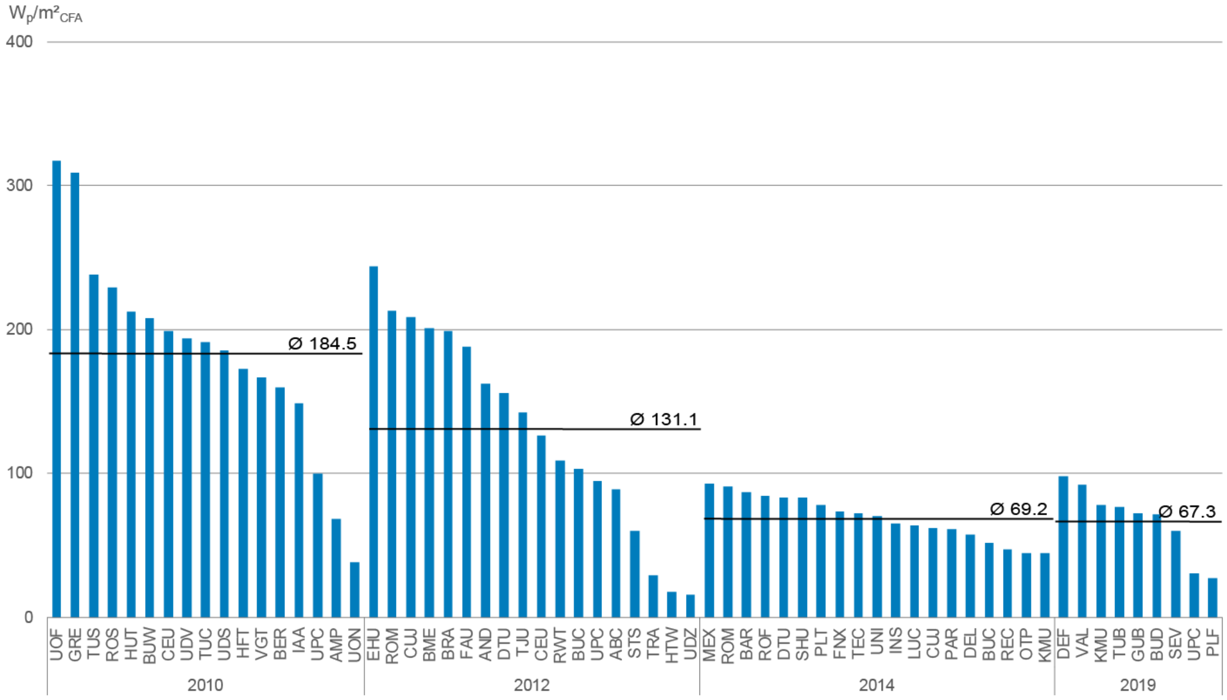


Figure 94: Correlation between the installed power of the PV systems and the conditioned net floor area of the houses in the European competitions in 2010, 2012, 2014 and 2019. The relevant information is not available for all houses. Source: S. Hendel, University Wuppertal

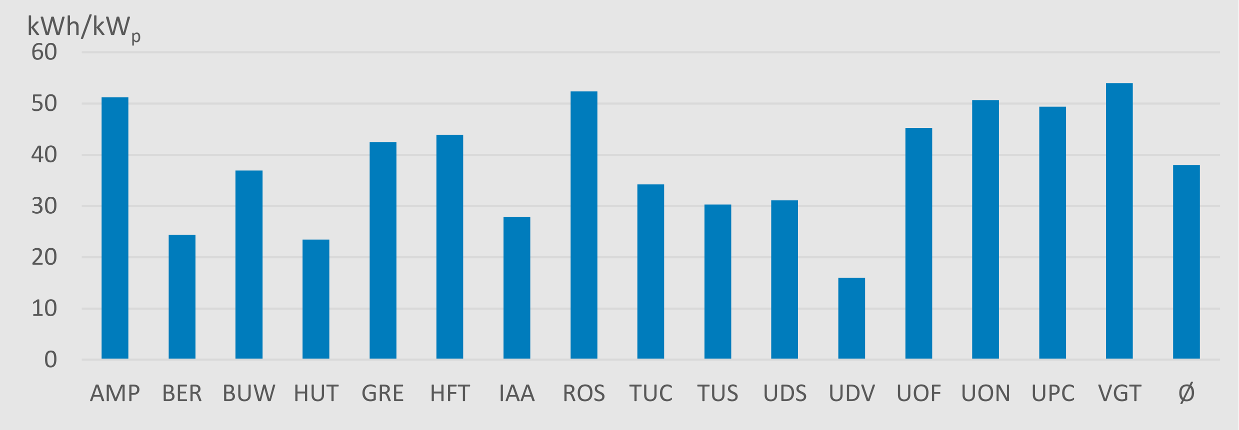


Figure 95: Specific yield of photovoltaic systems during the competition period of 10 days in relation to the installed capacity at SDE 2010 in Madrid. The average yield was 38 kWh per kW_p installed power. The differences are a result of the quality of system technology, electrical adjustment and the angle and orientation of the various systems. Source: University Wuppertal

Table 7: Average PV system sizing in the European editions of the Solar Decathlon. Source: University Wuppertal

		2010	2012	2014	2019
Installed power	kW_p	9.0	7.4	4.7	4.5
Installed power per conditioned house floor area	W_p/m^2_{cfa}	184.5	131.1	69.2	67.3

The technical and architectural examples of photovoltaic systems on SDE buildings support the growing market for such systems on buildings in Europe. Such systems are a central element of the European Energy Roadmap. The vision in the Roadmap is for almost all electricity to come from renewable sources by 2050. According to a survey by the European statistical office eurostat, renewables generated about 30% of electricity in the 28 EU countries in 2016 [eurostat 2019]. In Germany, the figure was already 48% by 2019, with solar power generation accounting for 9% [energy charts 2020]. In light of the competition for land for agriculture and significantly higher costs for ground-mounted systems, the expansion of photovoltaics on buildings is a central element of the European energy strategy.

The examples implemented with the SDE houses help to increase acceptance of photovoltaic solar energy use in buildings amongst visitors to the competitions and in reporting. They showcase a wide range of design and integration options for solar modules, and also use a number of multipurpose components. In addition to design aspects, competitors need to consider competition for space and function in buildings, which otherwise reduces the space available for solar power use. Examples are the combination of solar cells with shading or as part of glazing to make use of daylight. Hybrid systems of photovoltaics and solar collectors for thermal solar energy use are also used. This allows the absorbed heat at the solar panels to be utilized and the solar cells also to be used for nocturnal radiation cooling to cool water. The reduced module temperature may increase the efficiency of power generation, depending on the technology used. The following pictures show examples of the multi-purpose use of solar power systems and the application of new technologies. A good overview of systems available on the market is provided by the www.solarintegrationsolutions.org information platform, which was created as part of research by the International Energy Agency (IEA).

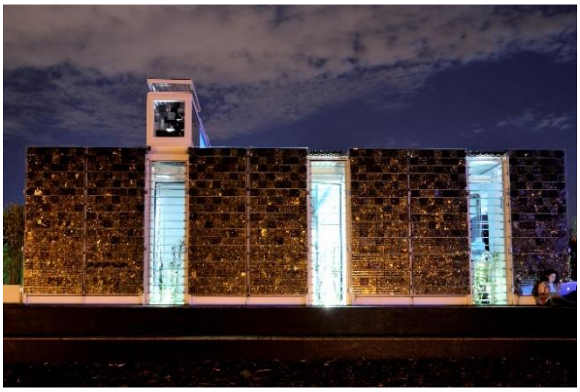


Figure 96: home+ (HFT) at SDE 2010 is a good example of the visible use of crystalline PV modules over a large area. Modules were integrated into the roof and also into the facade of the building, where coloured cells were part of the design. The PV areas together are about twice as large as the floor space. Source: [sde flickr]

Figure 97: The Armadillo Box created by the French team (GRE) at SDE 2010 also made wide-scale use of photovoltaic systems. The concept used PVT hybrid modules, which covered the roof and the upper section of the building. The solar "hood" on the top of the building is not directly attached to the roof structure and is therefore extremely well ventilated. Source: SDE Flickr, by Javier Alonso Huerta [sde flickr]

Figure 98: At SDE 2014, installed PV system capacity had already been limited to 5 kW$_p$. One example of the relatively small PV systems at the competition is the DTU 2014 house. Individual modules were integrated into the glass roof of an outer buffer zone. Source: SDE Flickr, by Valeria Anzolin and Jason Flakes [sde flickr]

Figure 99: Another example of subtle PV system integration is the OTP 2014 house. Here, modules were only installed on the roof and were almost invisible to the visitors. Source: SDE Flickr, by Valeria Anzolin and Jason Flakes [sde flickr]

Figure 100: The solar cells in the PAR 2014 house use fluorescent plastic (PMMA) to focus light on solar cells at the edges using total reflection. Source: SDE Flickr, by Valeria Anzolin and Jason Flakes [sde flickr]

Figure 101: Thin-film modules in the INS 2014 house enable integration into the building envelope, which consists mainly of a membrane. Source: SDE Flickr, by Valeria Anzolin and Jason Flakes [sde flickr]

Figure 102: PVT hybrid modules form the roof of the Med in Italy house (ROME 2012). Source: SDE Flickr [sde flickr]

Figure 103: Single-axis tracking concentrating PV using Fresnel optics at the Sumbiosi house at SDE 2012. Source: University Wuppertal

Grid-connected operation of the SDE houses ensures a power supply even at times when too little or no solar energy is available. This reflects standard practice in Europe. However, it means that the proportion of solar energy generated by the building that the building directly uses itself (self-consumption rate) and the degree of self-sufficiency (proportion of electricity consumption covered directly by the solar power system) remain comparatively low. A large amount of solar power is fed into the grid, and power is then also taken from the grid when required, most often in the early hours of the morning and at night. The situation can be improved by storing the electricity generated in batteries [county 2020-2]. The objective is to balance out daytime and night-time power, not longer-term or indeed seasonal storage. However, altering self-consumption is the priority, as any form of energy storage involves losses. Storage losses of around 10 % for short storage times are currently typical. Depending of the overall electricity supply system on a district, local, regional, national or broader level feeding in of excess electricity might not be called a disadvantage, if it comes at the right time, seen from the view point of the grid.

In European building practice, batteries are still rarely used because of their high acquisition costs. The falling costs of electricity storage – primarily a result of growing demand in the mobility sector – together with rising electricity prices for end customers, lower payments for electricity fed into the grid and subsidy schemes that vary from country to country are leading to the slow development of the market. It is therefore an advantage that the houses in the more recent SDE competitions use this technology in a wide variety of ways to investigate the functionality and the significance. These include adapted, approved inverter concepts that support such system concepts.

Table 8 provides an overview of the battery technologies and storage capacities used. In 2010, all batteries used were lead-acid based, but teams in later competitions increasingly used lithium-ion and lithium-ion/iron-phosphate batteries. The latter show advantages with respect to fire protection and the correlated danger. Typically, no special measures were undertaken for fire protection at the location of the batteries inside the buildings and no extra ventilation was provided. Batteries were allowed as part of the energy concepts in all European competitions to date, but how they were scored differed. In 2010, for example, almost no batteries were used, although they were in some cases documented in the energy concepts of the buildings. A common design would be for around half of the houses' daily electricity consumption. An average total load of 314 W in the household electricity circuit at SDE 2014 would mean a necessary usable storage capacity of 3.75 kWh. As the calculations in Figure 104 show, this roughly doubles the self-consumption rate and self-sufficiency. The sizing in the SDE competitions was generally slightly larger, which offered benefits in terms of points. In standard building practice, cost-effectiveness considerations usually result in smaller systems [garcía-Domingo 2014]. The rules of the SDE competitions in 2014 and 2019 promoted the use of batteries as the avoidance of load peaks and network load (power peaks, house adjustment to network load state) and matching demand and consumption (temporary generation-consumption correlation) had a positive effect on the achievable score.

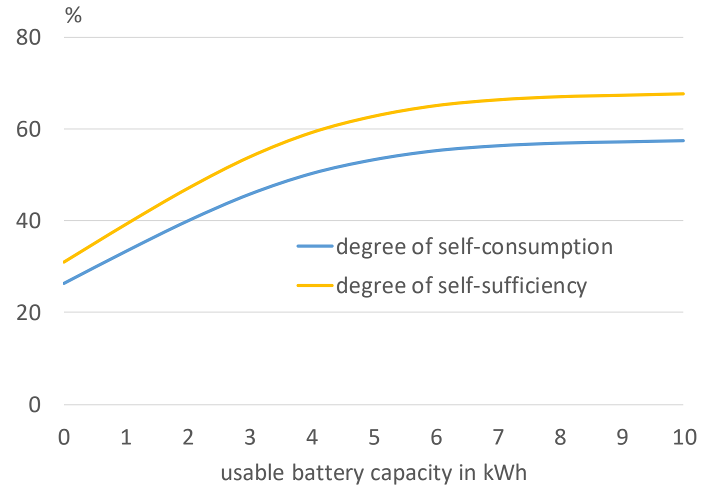


Figure 104: Relationship between the degree of self-consumption /degree of self-sufficiency and battery capacity for a small residential building with annual household electricity consumption of 2,750 kWh, a heat pump, a solar thermal system and a 5 kW_P solar power system. The data are based on simulations for a site in Germany. Source: University Wuppertal

Table 8: Batteries used in SD houses. Only teams for which documentation about the batteries was available are listed. Source: University Wuppertal

Edition	Team	Battery Type	Capacity in kWh
2010	BER	Lead-acid	
	BUW	Lead-acid	7.2
	CEU	Lead-gel	5.5
2012	CUJ	Lithium-ion	5
	CEU		6
	ABC		
	AND	Lead-acid	
	HTW		
	TRA	Lithium-ion	5
2014	BUC	Lead-acid	5
	KMU	Lead-acid	6
	LUC	Lithium-ion	5
	OTP	Lithium-ion	5.5
	REC	Lead-acid	5.28
	ROF	Lithium-ion	4
	ROM	Lead-acid	4
	UNI	Lithium-ion	5.76
2019	BUD	$LiFePO_4$	6
	DEF	Lithium-ion	5
	GUB	Li-NMC	6.5
	KMU	Lithium-ion	6
	MIH		6
	PLF	$LiFePO_4$	1.2
	SEV	Lithium-ion	6.6
	TUB	$LiFePO_4$	5.5
	VAL	$LiFePO_4$	6

Figure 105: Four externally mounted batteries (bottom) with lead-acid technology at an SD house at SDE 2012, Source: K. Voss, University Wuppertal

Figure 106: Externally mounted battery box (left-hand box) with lithium-ion technology at an SD house in the US competition in 2017. The capacity is listed at 13.5 kWh, Source: K. Voss, University Wuppertal

Figure 107: Small battery pack with lithium-ion technology as part of indoor house installation at the SD house of the MOR team in the SDE competition in 2019, Source: K. Voss, University Wuppertal

3.2.2 Solar Thermal Systems

An increase in solar thermal energy use would appear important in the light of the growing significance of domestic hot water in the heat balance of energy-efficient buildings: whilst efficiency measures to reduce demand for space heating and cooling are having an impact, the demand for heat for domestic hot water still remains constant. The required temperature level for domestic hot water is also higher than in the case of floor heating for space conditioning as typically implemented with heat-pump-based systems. Solar thermal system can increase the annual COP of heat-pump-based heating systems by taking over the main fraction of the higher temperature heat demand.

Small-scale solar water heating systems and solar combi systems for combined hot water preparation and space heating for detached single-family houses and apartment buildings, for multi-family houses, for hotels and for public buildings represent more than 90% of annual installations worldwide [iea shc 2019]. This traditional mass market has come under considerable pressure in Europe over the past few years. One reason is the drastic decrease in the price of PV systems while the prices of solar thermal systems remain more or less constant. Another aspect is the relatively complex system technology compared to the simplicity of grid-connected PV systems. Key elements are energy efficient thermal storage and suitable hydraulics and controls together with high system integration with less risk of installation failures [haeberle 2020].

Unlike PV, solar thermal systems almost always require storage in the given building. This is because excess heat cannot be stored in a public grid for later use. This would only be the case with heat networks, which have not to date been implemented at the SD villages. The storage together with the heat load is also the basis for the sizing of the collector area. Unlike with PV, this cannot flexibly be adapted to architectural requirements, for example a design that covers the entire roof. The usual system sizes for small single-family dwellings today are 4 m² for domestic hot water only and 10 m² for typical solar combi systems. In the DHW case 1 m² per person is a typical system size, corresponding to an indicator of 0.02 collector area per m² floor area. Many systems with standard collectors in SDE houses are larger (refer to Table 9). This indicates the broader use of the systems and/or in some cases the support from the system manufacturers to overcome the economic disadvantage of large systems. Typical hybrid collectors are particularly larger and concentrating collectors are particularly smaller. Thermal storage was mainly realized by insulated hot water tanks. Some teams experimented with phase change materials or thermo-chemical heat storage to achieve a higher storage density and less thermal loss. The large variety of storage volumes reflect the diversity in system integration.

In contrast to photovoltaics, solar thermal systems are not a compulsory part of houses in the competition, but almost all homes apply solar collectors (2010: 76%, 2012: 94%, 2014: 100%, and 2019: 70%). This reflects the high acceptance and market penetration of such systems in building practice, especially for small, new-build residential homes. Unlike for PV, there has to date been no measurement of the yield in the competitions, which would in this case be the heat yield. As a consequence, no information about the operation and performance of the systems can be evaluated from SDE monitoring data.

In reflection of the market situation in Europe [iea shc 2019], many teams apply standard flat plate or vacuum tube collectors. On the other hand, a variety of specialized collectors are considered such as uncovered absorbers, drain back systems, solar thermal concentrators, solar air collectors and many forms of hybrid collectors. Another aspect that reflects the market situation is that most of the systems are installed on the roofs of the buildings, on flat or inclined roofs. The few examples of façade integration are for solar combi systems that also contribute to heating or for hybrid collectors. As SDE is held during the summer months, such systems are essentially not a productive way of improving a team's score in the monitored energy performance. Moreover, façade integration of solar thermal collectors still remains a difficult architectural task. The standard systems available on the market are typically not designed to be directly visible, but teams do try to experiment with convincing approaches (Figure 110, Figure 113).

As in actual building practice, PV and solar thermal systems are competing for the areas on the building envelope exposed to sunlight. This is apparently also influencing the SDE teams. Due to the reduction in permitted installed power for PV in SDE 2012 and 2014 artificially more space was made available and more solar thermal systems were applied. Another way to resolve competing space requirements is to combine electrical and thermal solar power systems. This leads to so-called PVT collectors (photovoltaic thermal). SDE demonstrates a large number of examples. Around 1 million m² of such systems have already been installed in Europe [iea shc 2019]. Most of these systems are based on PV modules with air or water cooling at the back without additional glazing at the front to reduce heat losses. Without additional front glazing the focus is the generation of solar power. Many SDE competitors choose this PVT system option, some use the thermal circuit behind the panels for radiative cooling in the night. This option is possible in the case of flat mounted systems and a climate with mostly clear summer skies. Still the cooling contribution remains very limited. Adding an air gap and a glazing or plastic cover in front increases the temperature level of the useable heat, but decreases the power output mainly due to higher refection losses. Such collectors may generate heat on the temperature level suitable for DHW whereas unglazed collectors may just preheat the water or work as heat source for a heat pump [herkel 2020].

A major advantage of hybrid systems is the architectural harmony of solar power and solar thermal systems. This avoids the need to establish two technical systems with different appearances on a roof or façade. Hybrid collectors are still the subject of research and pilot applications [iea shc task 60].

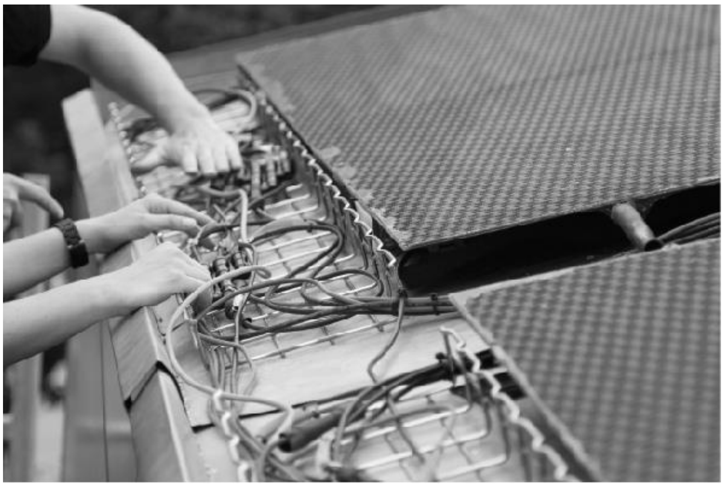


Figure 108: Custom developed PVT roof element from the “Fold” house of the DTU team in SDE 2012 during installation. Besides the wiring, the picture shows the water pipe behind the panel responsible to transport the heat absorbed from the panel to the storage tank. Source: Danish Technical University DTU, SDE 2012, DTU Jury Report

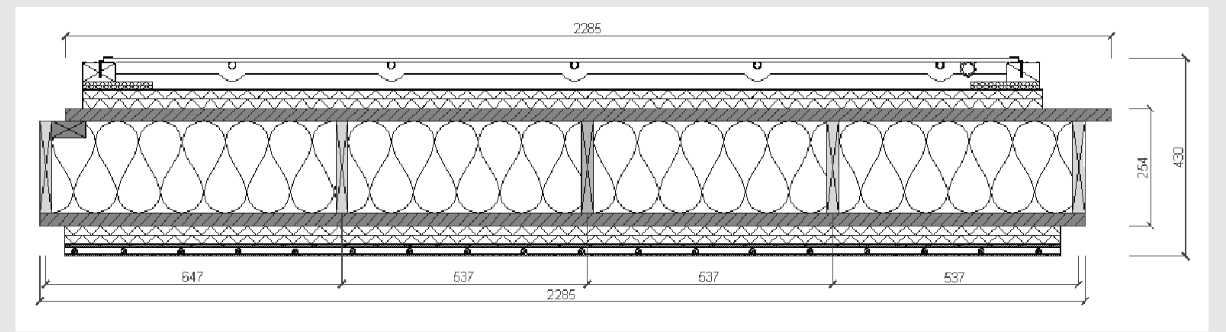


Figure 109: Cross section and installation of a PVT roof element from the “Fold” house of the DTU team in SDE 2012. Source: Danish Technical University DTU, SDE 2012, DTU Project Drawings

Table 9: Solar thermal systems implemented in the SDE homes and associated properties. Source: University Wuppertal

CFA: conditioned floor area. The abbreviations of the team names are based on those used on the building competition knowledge platform.

edition	team	collector type	position				size	storage volume	spec. collector area	storage per collector area
			flat roof	inclined roof	facade	other	m²	litre	m^2/m_{cfa}^2	litre/m²
2010	AMP	Hybrid Parabolic Concentrator		1						
	BER	Flat Plate Collector		1			8,4	450	0,16	54
	BUW	Vacuum Tube Collector			1		6,0	250	0,12	42
	CEU	Concentrating Collector + Hybrid PV	1					200		
	GRE	none								

edition	team	collector type	position				size	storage volume	spec. collector area	storage per collector area
			flat roof	inclined roof	facade	other	m²	litre	m^2/m_{cfa}^2	litre/m²
	HFT	Vacuum Tube Collector + Hybrid PV	1				6,6	300	0,13	45
	HUT	none								
	IAA	Hemispherical Solar Collector		1	1		3,2		0,06	0
	TUC	Vacuum Tube Collector		1				400		
	TUS	Vacuum Tube Collector + Hybrid PV		1	1			270		
	UDV	Vacuum Tube Collector		1				200		
	UDS	Unglazed Flat Plate Collector	1							
	UOF	none								
	UON	Flat plate	1				2,3			0
	UPC	Flat Plate			1		6,9	290		42
	VGT	none								
	Σ, Ø		5	6	4	0	5,6	296	0,11	53
2012	ABC	Solar Thermal Concentrator	1				1,0	180	0,01	
	AND	Flat Plate Hybrid	1				4,0	300	0,06	75
	BME	Hybrid PV	1		1			150		
	BRA	Vacuum Tube Collector		1			5,4	300	0,10	55
	BUC	Flat Plate		1			4,1	200	0,05	49
	CEU	Vacuum Tube Collector	1				7,8	200	0,14	26
	CUJ	Flat Plate				1	6,0	420	0,11	70
	DTU	Hybrid PV		1			70,0	180	1,19	3
	EHU	Flat Plate	1				2,2	110	0,04	50
	FAU	Flat Plate		1			2,6		0,05	
	HTW	Hybrid PV	1				57,6	300	0,85	5
	ROM	none								
	RWT	Vacuum Tube Collector	1				13,0	400	0,21	31
	STS	none								
	TJU	Flat Plate Hybrid	1				6,4	400	0,10	63
	TRA	Flat Plate Hybrid	1				13,0	180	0,19	14
	UDZ	Flat Plate Hybrid		1			33,4	600	0,53	
	UPC	Vacuum Tube Collector, Air Collector			1		4,0	400	0,09	
	Σ, Ø		9	5	2	1	15,4	288	0,2	40

edition	team	collector type	position				size	storage volume	spec. collector area	storage per collector area
2014	ATL	Flat plate		1			6,0			
	BAR	Flat plate	1				2,5	600	0,02	240
	BUC	Vacuum Tube Collector	1				6,0	700	0,10	117
	CUJ	Flat plate	1				6,0	420	0,08	70
	DEL	Flat plate		1			5,4	300	0,06	56
	DTU	Flat plate		1			4,4	180	0,07	41
	FNX	Flat plate		1			2,4	150	0,05	63
	INS	Vacuum Tube Collector				1	3,8	220	0,05	58
	KMU	Vacuum Tube Collector	1				4,0	300	0,04	75
	LUC	Vacuum Tube Collector	1				4,5	364	0,06	81
	MEX	Vacuum Tube Collector	1				4,0	300	0,08	75
	OTP	Vacuum Tube Collector		1			3,9		0,04	
	PAR	Flat plate				1	6,0	200	0,12	33
	PLT	Flat plate		1			4,7	300	0,08	64
	REC	Vacuum tube, drain back	1				9,8	303	0,09	31
	ROF	Vacuum Tube Collector	1				3,0	235	0,05	78
	ROM	not specified		1			1,6	300	0,03	188
	SHU	Vacuum tube, tank integrated	1				4,5	200	0,07	44
	TEC	Flat plate		1			2,2	350	0,04	159
	UNI	Vacuum Tube Collector		1			13,6	300	0,19	22
	Σ, Ø		9	9	0	2	4,9	318	0,07	83
2019	BUD	none								
	DEF	Flat Plate Hybrid			1		13,0		0,25	
	GUB	Flat Plate Hybrid	1					260		
	KMU	Flat Plate	1				5,7		0,09	
	MIH	none								
	PLF	Vacuum Tube Collector			1					
	SEV	Vacuum Tube Collector	1				7,8	300	0,10	38
	TUB	Flat plate absorber for a heat pump		1			1,6	250	0,02	156
	UPC	none								
	VAL	Flat Plate Hybrid		1			5,0	220	0,09	
	Σ, Ø		3	2	2	0	6,6	258	0,1	97

Figure 110: Concentration solar thermal system on the roof of a house at SDE 2010. Source: K. Voss, University Wuppertal

Figure 111: Façade-mounted flat plate collectors at a house at SDE 2014, Source: K. Voss, University Wuppertal

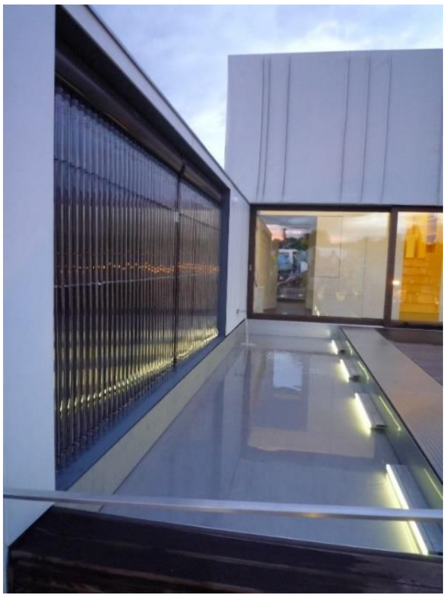


Figure 112: 6 m² vacuum tube collectors mounted vertically in an external wall of the BUW team home at SDE 2010 in Madrid. Source: K. Voss, University Wuppertal

Figure 113: Vacuum tube collectors mounted in front of a window in the façade of the INHABITAT team home at SDE 2019 in Szentendre. Besides hot water generation, the system allows some daylighting and generates shade to the window. Source: K. Voss, University Wuppertal

3.3 Energy Efficient Appliances

In the discipline, "house functioning" refers to the houses' electrical energy consumption for household appliances, lighting, consumer electronics and other small appliances. There are also the evening events at which the teams visit each other for dinner, requiring the additional operation of light and appliances. Household electricity consumption at SDE is usually higher than electricity consumption for heating, ventilation, cooling and domestic hot water (Figure 114). This is due in part to the moderate climatic conditions during the competition periods in Europe and the additional use of ambient heat as the major heat source for the heat pumps alongside electricity.

If we look at the scores in the energy contest, the houses have largely used highly energy-efficient appliances. Figure 115 shows the evaluation of the buildings' household electricity consumption at SDE 2014. The 2014 organiser was the first to introduce electricity recording by consumption sector. The average power was 314 W; at the SDME in Dubai 2018, it was 450 W. Extrapolated over a whole year that is 2,750 kWh and 3,940 kWh respectively. In building practice, the standard figures per dwelling unit in Europe vary widely. This is because of the size of households (number of inhabitants) and different fittings/equipment and living habits. Statistics show values per household ranging from 1,000 kWh (Romania) to over 5,000 kWh (Sweden) [odyssee-mure 2020]. For the net zero energy and energy plus buildings implemented in Germany as part of the research initiative Effizienzhaus Plus, the averages for comparatively large single-family dwellings were 2.16 W per m² of living space [bmi 2018]. Taking into account the average living space of 78.3 m² at SDE 2014, the comparable figure is 4 W/m². The fact that the figure is much higher in terms of area for the houses at SDE is because they are fully fitted but have a small living space (see separate report on Building Design & Construction). This example shows the negative implications for energy consumption if the European trend towards smaller household sizes continues.

Nearly all teams demonstrate very energy-efficient household appliances (Figure 116) and LED lighting in their buildings to reduce consumption and thus improve the energy balance (Figure 117). In some cases, special solutions were also used to replace the operation of equipment (e.g. dryers, Figure 119) or to substitute artificial light with daylight despite the lack of windows, Figure 118 [frascarolo 2014].

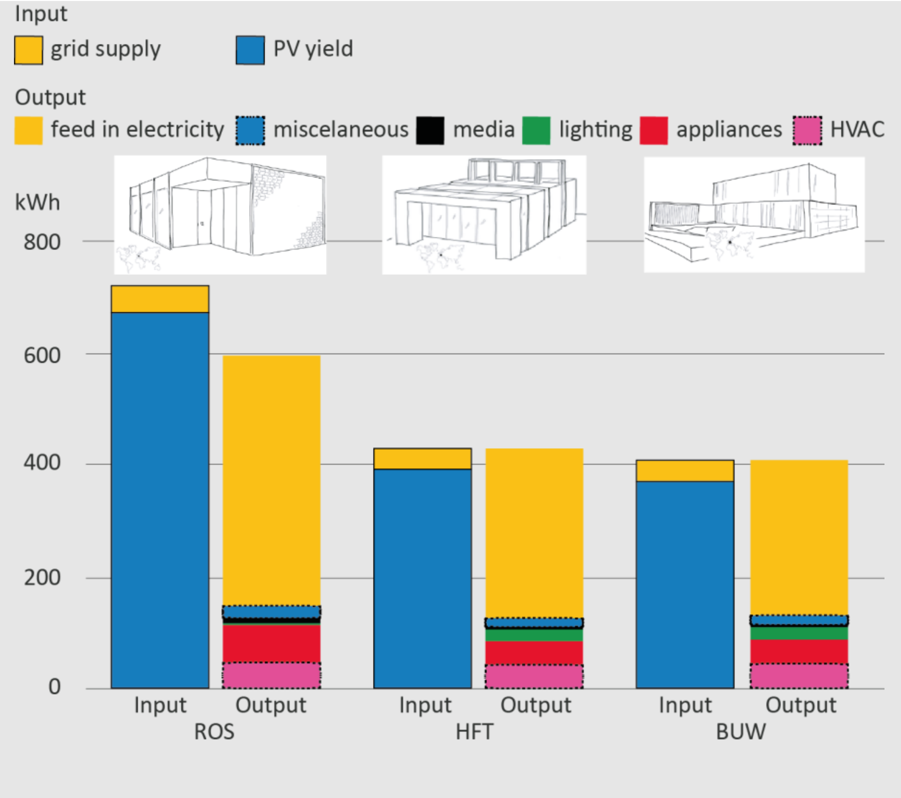


Figure 114: Measured energy consumption and energy generation of three SD houses. The figure shows the cumulative energy data of three German houses during the 10 event days of SDE 2010. Source: S. Hendel, University Wuppertal

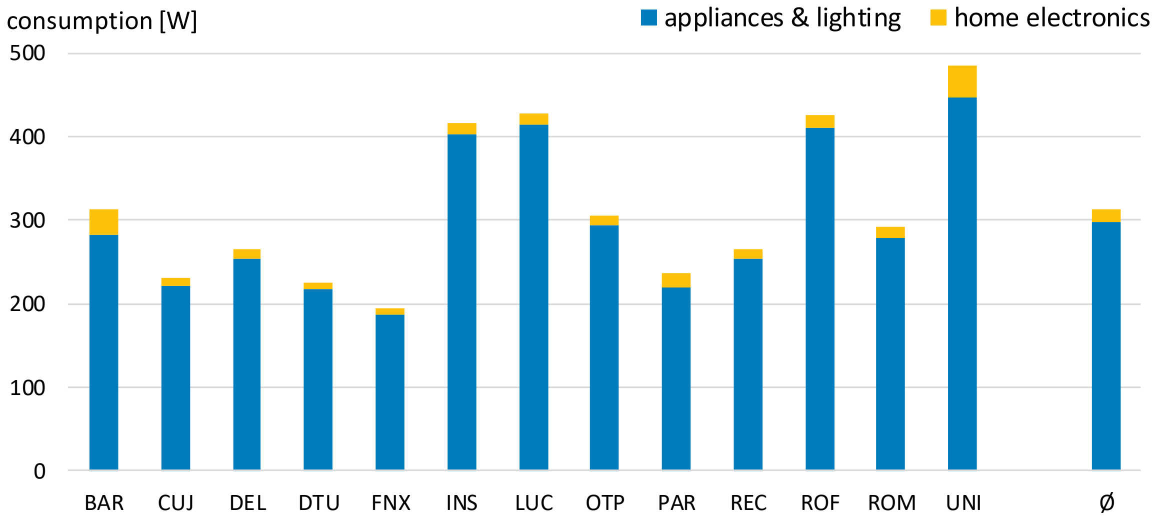


Figure 115: Average power for household appliances, lighting and small electrical appliances in the competition period at SDE 2014. Source: M. Stark, University Wuppertal

Figure 116: Example of the use of market available, energy-efficient appliances (SDE 2012). Source: University Wuppertal

Figure 117: Energy-efficient lighting by LED systems within an acoustic ceiling and integrated movement sensing (SDE 2010). Source: University Wuppertal

Figure 118: Daylight luminaires partly substitute artificial lighting in an internal bathroom (SDE 2012). Source: University Wuppertal

Figure 119: Integration of laundry drying in the circuit of the central ventilation system to substitute the operation of a dryer in the house of Team Lausanne at SD US 2017. Source: University Wuppertal

3.4 Heating, Ventilation, Air Conditioning and Domestic Hot Water

As all buildings at an SD are all-electric homes, all have heat pumps or compression refrigeration machines for active heating or cooling and for hot water. In the light of the growing use of renewable energies in the electricity grids of many European countries, the focus on electricity as an energy source reflects a current trend. Heat pumps are increasingly becoming the standard supply option in new buildings and are replacing the local combustion of fossil fuels such as natural gas. In some countries (Denmark), that combustion option has already been banned. The SDE houses and their energy concepts are therefore of great practical relevance in Europe. SDE 2021 opens the energy supply side for other options within a real building energy concept for the first time at an SDE event. The demonstration units must not have a heat and cold supply unit. Due to the foreseen weather conditions during the competition time, the houses are expected to run within comfortable indoor climate without active heating or cooling [sde21 2019]. According to the heat transfer fluids used in the secondary side of evaporator and condenser, the heat pumps used were categorized into groups such air-to-air heat pumps, air-to-water heat pumps, water-to-water heat pumps, water-to-air heat pumps, and other heat pumps. Using ground or ground water was not an option within the competitions, as teams were not allowed to modify the ground of the lot. The Danish Team “Fold” in SDE 2012 operates a buffer tank to “simulate” the performance of a ground heat exchanger-based heat pump system (see Figure 120). In principle, such systems are more effective (increased annual coefficient of performance due to more constant and more suitable temperature level of the source), but on the other hand it is more expensive to access the ground compared to ambient air. The lower investment is the major argument why ambient air heat pumps dominate the market.

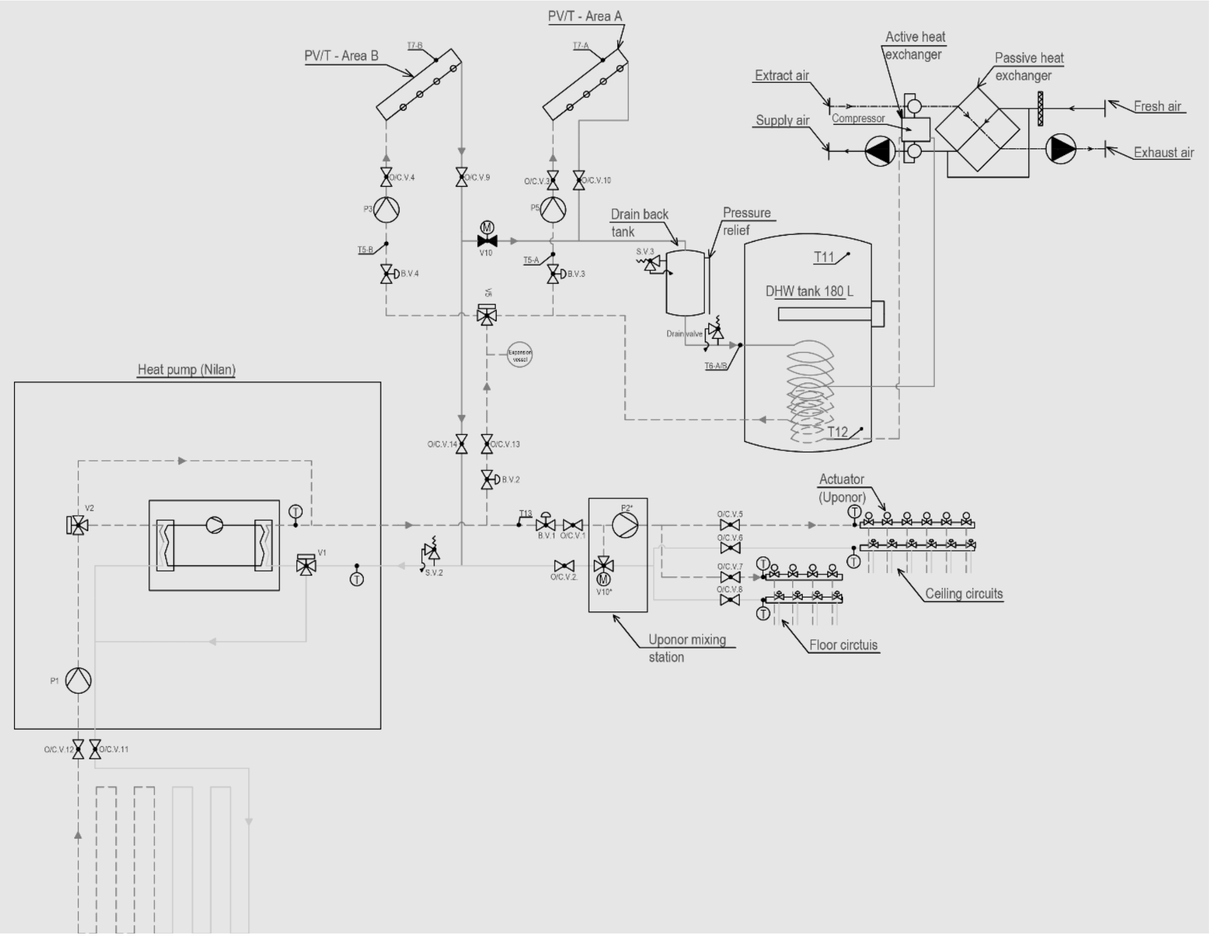


Figure 120: Layout of the solar assisted HVAC/DHV-System of the “Fold” home of the DTU team of SDE 2012. The heat pump operates with a ground heat exchanger. During the event this heat exchanger was ”simulated” by a buffer tank next to the house, as ground installations were not allowed. Source: Danish Technical University DTU, SDE 2012, DTU Project Drawings

Either thermal solar systems or hybrid collectors were to be hydraulically integrated in line with the system concept. For reasons of necessary compactness, reversible units have generally been used, i.e. a single unit with both a heating and cooling function. The concepts implemented differ considerably: from combinations of standard units that are installed next to the buildings and supply the usual heating and cooling surfaces, to developments with a high degree of integration into the building ventilation system (compact ventilation units). The heat source in compact ventilation units is not outside air but instead the exhaust air after heat recovery from a mechanical ventilation system. In both concepts, the air is cooled to below the temperature of the outside air. For compact ventilation units, this means that the heat yield from the air flow must provide a sufficient heat source. This is usually only possible at the level of a passive house (space heating load max. 10 W/m²), which is not achieved by all SDE houses. The majority of SD buildings have a mechanical ventilation system, but not all.

Most heat pumps applied work with R410A as refrigerant. The teams have chosen very different dimensioning for the units. Whilst a number of teams work with compact units in a thermal power range of up to 2 kW, conventional split systems with almost 20 kW have also been used in the competition. The average installed heating capacity in SDE 2012 was about 5 kW (see Figure 121). In practice, units with higher power ratings allow the temperatures in the building to be adapted more quickly to requirements, but they also place a higher load on the power grid and are noisier and more expensive to purchase. At the 2021 European competition, days for the measurement of the indoor climate will, for the first time, be consistently separated from those with visitor traffic.

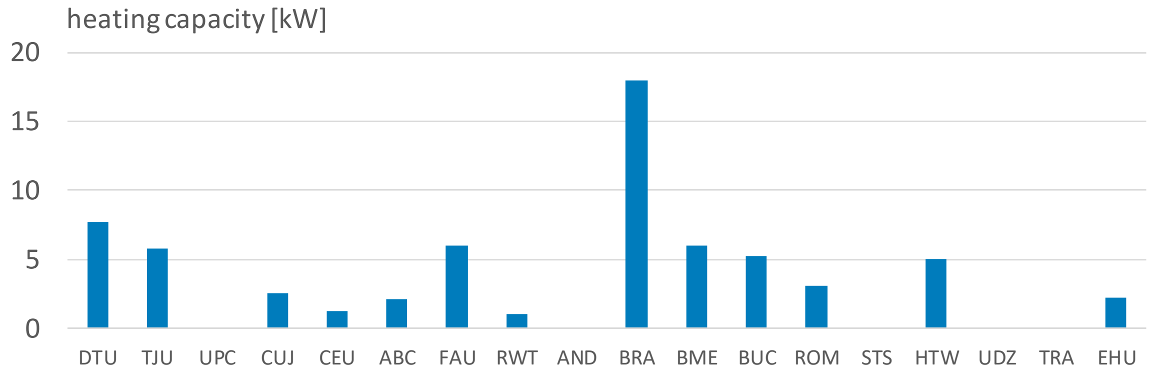


Figure 121: Installed heating capacity of the heat pumps applied in SDE 2012 based on manufacturer data sheets. Data are not available for all teams. Source: University Wuppertal

The figures for electricity consumption for HVAC/DHW over the competition period, using the example of SDE 2014, clearly show that it is not the building services engineering but rather household appliances that dominate consumption on locations with a moderate climate. The average for HVAC/DHW is 136 W compared to 314 W for household appliances. Unlike for the appliances, it is not possible to extrapolate annual consumption for the HVAC units as the climatic conditions on the competition days do not represent the annual average. However, the annual figures calculated do also show that household appliances generally account for the largest proportion of demand. The use of solar thermal systems and efficient heat recovery from exhaust air to heat up the supply air are also contributing factors to lower the remaining electricity needs for HVAC/DHW. This finding shows how the scenario for buildings in Europe will change if integrated efficiency concepts are implemented. This becomes a different story with the competition taking place in the Dubai climate as it was the case for SDME 2018. At that location the HVAC consumption made up half of the total consumption of about 1,000 W on average during the competition period. This reflects the simulation findings presented earlier.

While air-to-air heat pumps in conjunction with ventilation units transfer heat directly to (heating) or absorb heat from (cooling) the indoor air, air-to-water heat pumps operate with heating or cooling surfaces so that the lowest possible temperature differences compared to the indoor air are sufficient for operation. To heat drinking water, air-to-air heat pumps must also supply an additional water circuit unless there is direct electrical heating of drinking water. The storage sizes selected for this purpose are in the range of 200 to 600 liters.

Figure 122: Split system compressor outside a building at SDE 2014. Source: University Wuppertal

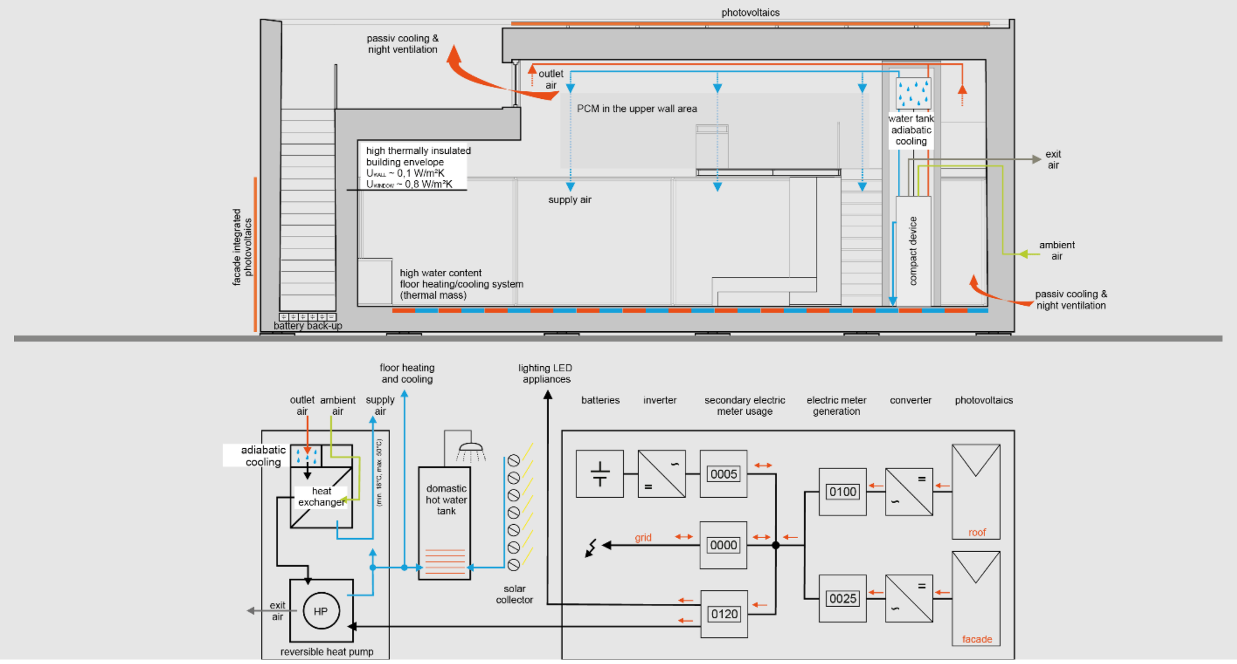


Figure 123: Full integration of a compact device for HVAC and DHW in the SDE house by Team Wuppertal at SDE 2010. The compact unit takes the waste air after ventilation system heat recovery as a heat source for heating mode. Heat is delivered as switchable to the supply air, floor heating and the DHW storage tank. The compact unit is integrated into the house interior with acoustic insulation all around. The unit was, however, found to be too noisy in operation during the night when people are sleeping in the house. Source: University Wuppertal

For many buildings in moderate climates, domestic hot water will in practice determine how systems in nearly zero energy buildings and "passive houses" are dimensioned. Whilst excellent heat and sun protection can keep heating and cooling capacities very low, and those requirements are usually met using large surfaces with small temperature differences to the indoor air, high temperatures are required for domestic hot water. For reasons of convenience and in line with the size of the storage tanks, water heating can therefore also result in high power consumption even over short periods of time. When operated for domestic hot water in particular, heat pumps have a comparatively poor coefficient of performance (ratio of heat output to electrical power consumption), which has a negative effect overall on the seasonal performance factor (ratio of annual heat yield to annual electricity consumption). The greater this effect, the greater the proportion of domestic hot water demand is in total heat demand. Solar collectors are therefore consistently used in many SDE buildings, as the right system design and operation in the competition can render water heating with a heat pump almost completely unnecessary. An IEA working group has researched and investigated such systems in depth in the light of their significant market relevance [iea shc task 44] [herkel 2020].

The performance of the heat pumps was not monitored in the competitions up to now but has partly been addressed in living labs of the participating universities following the competition. Within the competition, monitoring was limited to the power metering of the total HVAC circuit, but not in more detail than that. As already mentioned for the solar thermal systems, no heat output was monitored. No further performance analyses can be presented such as an investigation of the coefficient of performance in real operation compared to manufacturer data.

Even if there are no specific measurements to be evaluated for individual HVAC/DHW components, the houses in all SDE competitions have implemented a wide range of innovations in this area, not least for single-family dwellings and small dwelling units, i.e. small-scale buildings:

- Ventilation heat recovery with high efficiency (> 85%)
- Direct and indirect evaporative cooling
- Advanced thermal storage with phase change material (PCM)
- Heat recovery from waste water

- CO_2-based heat pumps
- Absorption heat pumps
- Cooling ceilings with integrated PCM
- …

The publication of Ma et.al. in the 2019 Journal of Cleaner Production presented a statistic overview on HVAC technologies applied in SD competitions worldwide from 2002 to 2018 [ma 2019]. Table 10 extracts some of the analysis regarding the competitions in Europe until 2014. The analysis in some points differs from own investigations due to unclear separation of topics. For example, the use of solar thermal for space heating may be partly not clearly separated from solar thermal use in general. Some PV systems are partly expanded to hybrid collectors and might be not listed as solar thermal applications. In general, the publication underlines, that deep investigations regarding single technologies are not possible beside statistics. Testing and monitoring of technologies has not been part of the Solar Decathlon up to now.

Table 10: Statistical analysis of the HVAC technologies used in the SDE 2010/12/14 according to [ma 2019]

	Solar thermal space heating	Radiative cooling	Evaporative cooling	Desiccant dehumidification	Absorption/ adsorption cooling	Phase change material	Ventilation heat recovery	Radiant heating	Radiant cooling
SDE 2010	41%	18%	29%	0%	6%	53%	77%	53%	59%
SDE 2012	50%	33%	22%	11%	6%	44%	78%	39%	33%
SDE 2014	65%	5%	15%	10%	0%	50%	90%	40%	35%
Heating & Cooling Technologies						Storage	Recovery	Delivering method	

The evaluation of these innovations is the responsibility of the relevant jury, and subsequent monitoring and development after the actual competition is the responsibility of the teams and their partners in industry.

Two practical aspects at the SDE competitions also illustrate the challenge of using heat pumps:

- Dense building development on the competition site focuses visitors' attention on noise emissions from the systems or system components installed there. Outside-air heat pumps and chillers outside in dense housing developments are in practice often at the centre of neighbourhood disputes when not dimensioned appropriately. This is particularly true when high system or unit output is required.
- When heat pumps were installed *inside* the SD buildings, for example as compact ventilation units, this clearly shows the problems of noise emissions when there are nearby bedrooms. In some cases, such problems pose limits on compact floor plans. In practice, separate, sound-insulated technical rooms and special measures to reduce the transmission of equipment noise around the installation area and the air ducts are required.

Both aspects are included in SDE as part of the jury evaluation for "Engineering & Construction". Measurements of equipment noise have been addressed in the rules for individual competitions, but not conducted or documented in practice.

Figure 124: Service room with heat pump and thermal storage in an SDE house in 2010 in Madrid. Source: University Wuppertal

Figure 125: Visible installed ventilation components above the windows – internal components of a split system at SDE 2014. Source: University Wuppertal

Figure 126: Mobile, planted duct to increase humidity in the dry summer climate in Madrid, SDE 2012, without active air conditioning. Source: University Wuppertal

Figure 127: Planted wall to increase humidity in the dry summer climate in Madrid, SDE 2010 without active air conditioning. Source: University Wuppertal

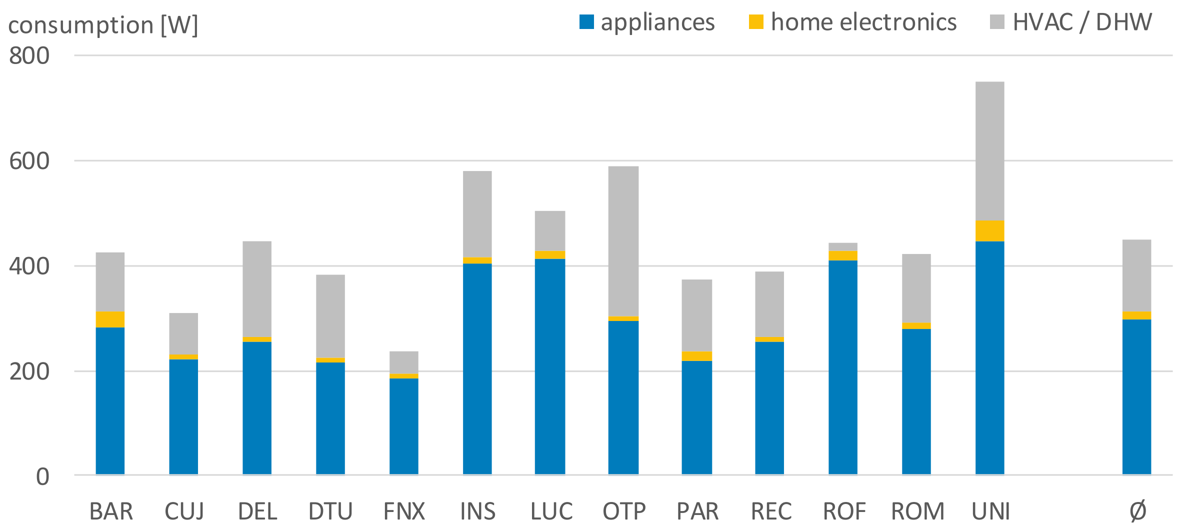


Figure 128: Average power consumption in the circuit for the HVAC and DHW systems compared to other loads of all houses during the competition period at SDE 2014. In all cases, the appliances dominate the energy consumption. Source: M. Stark, University Wuppertal

3.5 Controls

In most SDE houses, buttons and touch-panel operation have replaced the usual switches and controls. Various types of bus systems such as knx and EIB and wireless communication systems in conjunction with smart home systems are also used. These solutions have regularly sparked huge visitor interest as they are a contrast to familiar controls in building practice. Market penetration in Europe is still comparatively low. SDE 2021 will for the first time evaluate the user-friendliness of such interfaces as part of the competition. Guest teams will evaluate user-friendliness at evening events in the buildings using questionnaires and interviews [sde21 2019] [siow 2020].

Smart home system functions go far beyond energy and indoor climate management: billing, convenience, security, home entertainment, independence and social participation in old age, etc. However, specific examples from SDE relating to energy and room climate management include:

- Shared use of available information about the outdoor climate, the indoor climate, the operating states of technical systems and storage availability for energy-optimised system management.
- Daylight measurement and presence monitoring for lighting control
- Energy-saving control of air volume based on CO_2 measurement and targets.
- Information for users to facilitate energy-saving behaviour.
- Operation of devices over a standard interface.
- Integration of weather forecasts, simulation models and decision algorithms from neural networks into system controls.
- Consideration of energy consumption forecasts based on adaptive algorithms for user behaviour such as arrival times, periods at home and consumption peaks
- Flexible building-grid interaction: using information on the state of the public grid to decide on the operation of systems and storage systems. Electricity should, if possible, be purchased when it is available CO_2-free and otherwise not when it involves high emissions [iea Annex 67].

The use of smart controls involves additional consumption by the controllers themselves. This is of particular significance when it comes to controlling small levels of consumption – which is frequently the case in SDE buildings. In some cases, teams therefore use controls they have developed themselves on the basis of low-power components (e.g. Raspberry Pi...). Such innovations offer inspirations for the professional equipment market.

Figure 129: Typical low-voltage pushbuttons as part of the building automation system to replace classical switches for AC wiring (SDE 2012). Source: University Wuppertal

Figure 130: Turning knob to manually adjust the set point for a CO_2-controlled ventilation system (SDME 2018). Source: University Wuppertal

Figure 131: User interface for operating the HVAC system in the Tongji team house at SDE 2012. Source: University Wuppertal

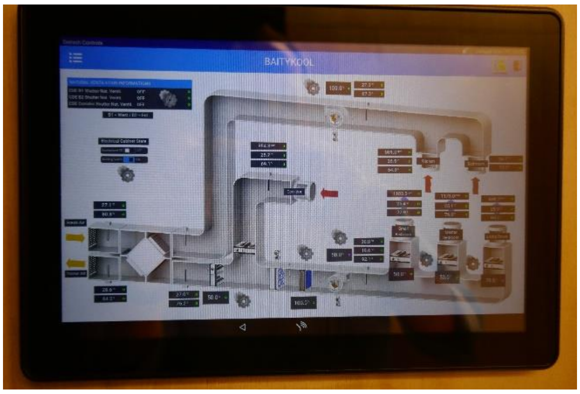


Figure 132: Graphic display of the building automation system for the Baitycool team at SDME 2018 in Dubai. Source: University Wuppertal

Assisting the manual control by the occupants with a suitable automatic control of solar shading and ventilation is a key issue to run a building with convincing thermal comfort, indoor air quality and low energy consumption. Summer thermal comfort is a key issue with regard to climate change [arranz 2014]. Indoor air quality becomes a challenge for buildings with almost airtight envelopes. SDE rules have specially addressed both issues since the beginning. The following two figures illustrate monitoring results for indoor comfort for selected buildings of SDE 2010. The challenge for the teams was the combination of visiting periods without scoring followed by scored periods during the same days. Large installed cooling, heating or even ventilation capacity was favourable to control the temperature quickly after visiting times to the required conditions for the following monitoring period. The challenge was particularly high for the most attractive houses visited by many people. SDE 2021 plans an event schedule with full separation of scored days for indoor comfort measurements and visiting days.

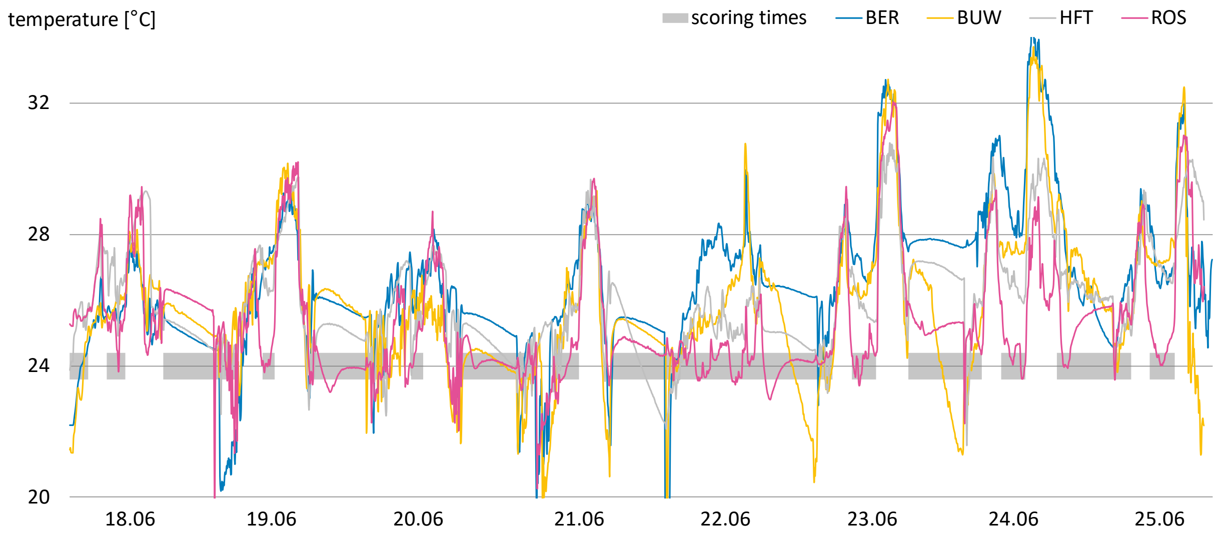


Figure 133: Example of transient indoor air temperature of four houses at SDE 2010. The grey bars mark the times when scoring takes place. Full points are gain for keeping the temperatures between 23°C and 25°C, reduced points up to 27 °C or down to 21°C. It was the task of the controls to operate the building in such a way as to maximize the score. Large installed cooling or heating capacity was favourable to control the temperature quickly after visiting times to the required conditions for the monitoring period. Source: University Wuppertal

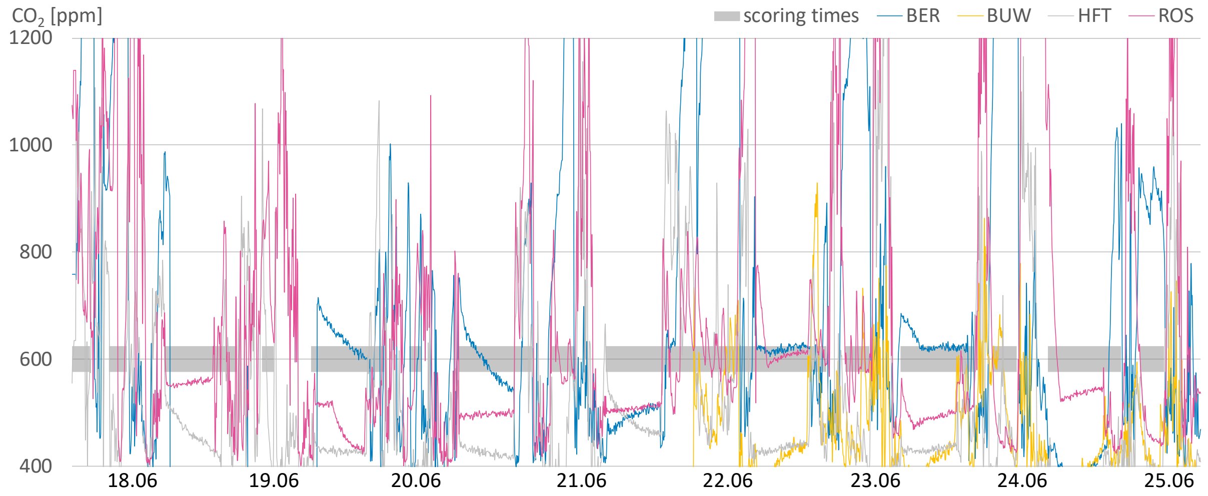


Figure 134: Example of transient indoor air quality (CO_2) measurements of four houses at SDE 2010. The sensor in the house of team BUW shows wrong results in the early days. Comparable to the figure before the grey bars mark the times when scoring takes place. Full points are gained for keeping the CO_2 level below 800 ppm, no points above 1,200 ppm. It was the task of the controls to operate the ventilation in such a way as to maximize the score. Source: University Wuppertal

3.6 Energy Balance and Building Grid Interaction

SDE houses should demonstrate how to balance out electrical consumption through solar power generation (net zero-energy buildings) and ideally also generate significant surpluses for grid feed-in (net energy plus buildings). An evaluation of monitoring data during the competition period shows whether or not this has been achieved. The graphs below (Figure 135, Figure 136) chart total generation and consumption during the competition period for all buildings in the two competitions in 2010 and 2014.

Details for SDE 2012 have been published in a special issue of the Energy and Buildings journal [rodriguez-ubinas 2014].

As Figure 135 explains, all buildings at SDE 2010 achieved a positive energy balance. This was due in part to favourable climatic conditions – lots of sunshine – during the competition period and to the size of the PV systems (up to 15 kW$_p$). Limiting the size to a maximum of 5 kW$_p$ significantly changes the balance at SDE 2014. As a result, not all houses achieve a positive balance although the electricity consumption is similar (N.B. scaling is different). Monitoring was more extensive at SDE 2014 and the feed-in and consumption balance is therefore also shown. The difference is the houses' own consumption of solar power they generate. Where one dot is directly above another (same consumption), the two relate to the same building. The distance between them indicates how well that house is covering its own demand. Buildings with batteries and intelligent control are at an advantage here. For small single-family dwellings with heat pumps and photovoltaic systems without battery storage, the self-consumption rate in practice is about 20 to 40 % for the year as a whole [bmi 2018]. The main reason why the rate is not higher is that large solar energy systems are required to balance out electricity consumption for the year overall. Large systems lead to large surpluses on sunny days, in particular during the summer months. At SDE 2014, the average self-consumption of self-generated solar electricity is 37 % with a range from 25 to almost 60 %. High figures represent buildings with comparatively small solar power systems, systems with different orientations or angles per house, battery storage and good energy management.

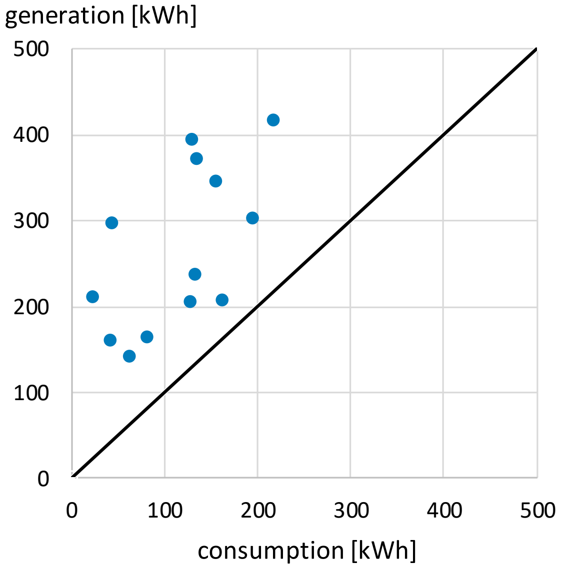


Figure 135: Electrical energy balance of all houses at SDE 2010 based on monitored data during the competition period. Houses with data points above the diagonal are energy plus homes: the generated power of all houses exceeds the consumption. Source: M. Stark, University Wuppertal

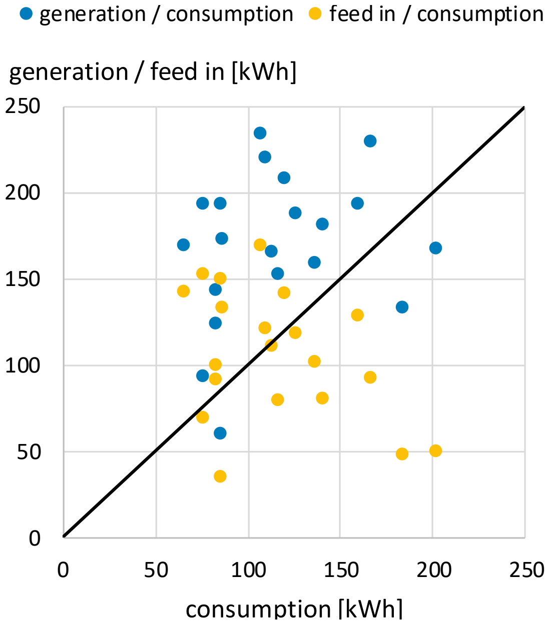


Figure 136: Electrical energy balance of all houses at SDE 2014 based on monitored data during the competition period. Besides the generation / consumption balance, the diagram shows the feed-in / consumption balance. Please note the change in the scaling compared to figure 2.46. Source: M. Stark, University Wuppertal

Figure 137 shows the superposition of electricity loads and electricity generation of all houses for SDE 2014. It shows the electricity profile over time for the entire solar village. The graph clearly shows the feed-in peaks of around 50 kW in the middle of the day on sunny days and evening peak loads of 25 kW. The evening peak loads can be considerably reduced by in-house battery storage, but clearly not completely balanced out. Feed-in to the batteries in the morning delays high feed-in until the batteries are recharged. In a development made up of houses with heat pumps (refrigeration machines) and heat accumulators (cold accumulators), controls could ensure that units did not start up at the same time. Such "intelligent control" on a district scale can balance the grid profile, reducing the load on necessary grid expansion in new housing developments.

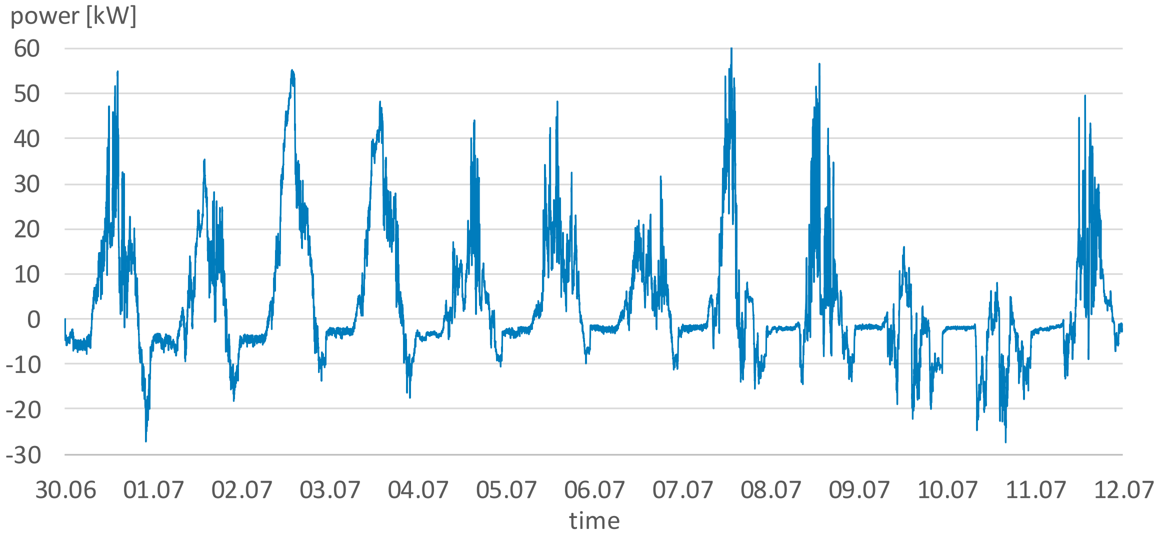


Figure 137: Superposition of the electric load and generation for all houses at SDE 2014. Negative numbers correlate to a load greater than the generation. This illustrates the transient status of the “solar village” grid. Source: M. Stark, University Wuppertal

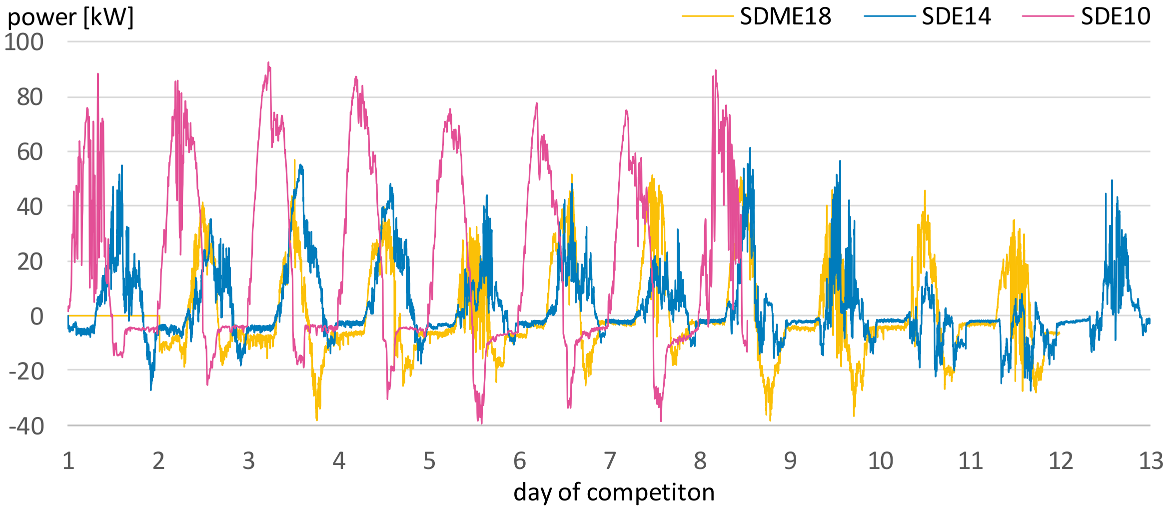


Figure 138: Superposition of the electric load and generation for all houses at SDE 2010 and 2014 together with data from the SDME in Dubai 2018. Data for SDE 2010 are only available for 8 days. Please note that the diagram compares the power balance from different competitions with different climates and different rules. Source: M. Stark, University Wuppertal

Figure 139: Typical grid access point at SDE 2014. Source: University Wuppertal

Figure 140: Small electric car with charging point as part of the houses' energy concept at SDE 2012. Source: University Wuppertal

Typical indicators for the analysis of the dynamic performance of solar powered homes are:

- Self-consumption: The ratio of the solar yield instantaneously used to cover the load in the house or stored in a battery. 100% indicates that all the solar yield is directly used and no electricity is fed into the public grid. This is the case for small installations in houses with high and continues consumption.
- Self-sufficiency: The part of the load that is instantaneously covered by the solar yield or the battery. (Note: In this interpretation the battery should not be used to buffer power from the grid). 100% indicates that the solar system always generates at least the power needed in the house. As this is not possible during night, battery storage is a precondition.

Both indicators are sensitive to the data resolution. Real numbers are direct meter readings. Due to the monitoring concepts and the available resolution of the meter readings, the indicators for the SDE homes can only be calculated based on 1-minute resolution data, thereby documenting slightly higher indicators as real. Nevertheless, the following diagrams illustrate the advantage of battery storage with the example of the Team OTP house in SDE 2014 (capacity 5 kWh) compared to the house of the Team INS, not equipped with battery storage. Resulting from internal storage, less electricity is distributed to and drawn from the grid. Averaged over the competition period the degree of self-sufficiency is nearly doubled and the self-consumption increases by 60%. On the other hand, such results cannot be generalized as positive under today’s circumstances: As every form of storage creates losses it is in many cases better to feed excess power into the grid and consume it in a house in the neighbourhood as long as the majority of houses don’t have solar power supply. Thus the SD houses with battery storage anticipate a future with a much higher penetration of solar energy utilization in buildings than is the case today.

Figure 141: The team INS “Inside Out” house from SDE 2014. Source: K. Voss, University Wuppertal

Figure 142: The OTP “On Top” house from SDE 2014. Source: K. Voss, University Wuppertal

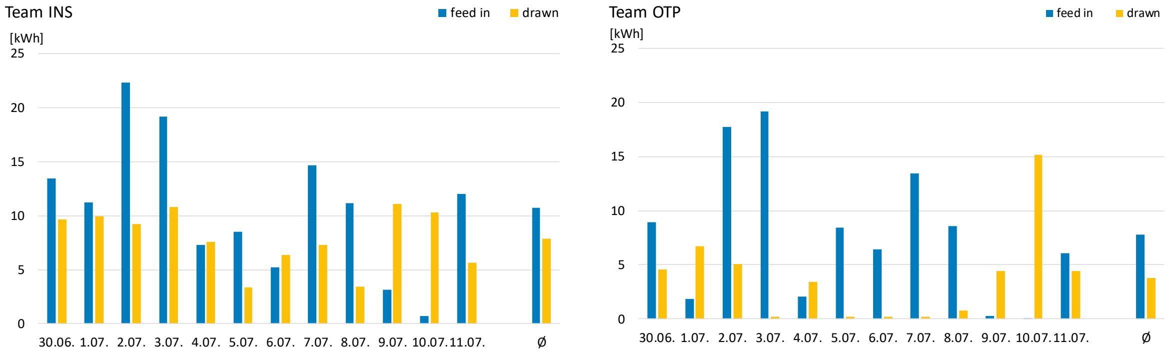


Figure 143: Comparison of the energy drawn from and energy feed into the power grid for two example buildings of SDE 2014. The OTP house (right diagram) uses a battery storage with a capacity of 5 kWh. Source: M. Stark, University Wuppertal

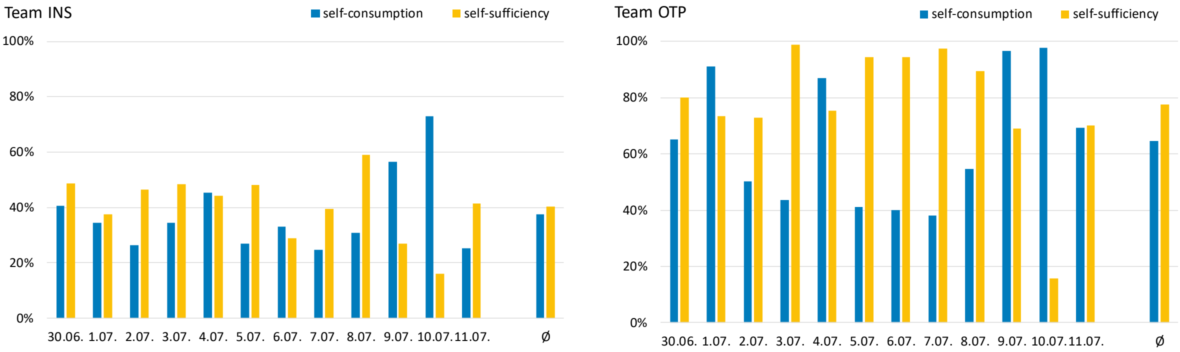


Figure 144: : Comparison of the indicators for self-consumption and self-sufficiency for two example buildings of SDE 2014. The OTP house (right diagram) uses a battery storage with a capacity of 5 kWh resulting in significantly increased indicators. Source: M. Stark, University Wuppertal

3.7 Conclusion

The chapter has summarized and analysed the information available from past competitions with a focus on the European editions. This includes the comparative compilation of the characteristic energy systems indicators as well as the compilation of the monitored energy performance data. The work was based on a systematic application of the building competition knowledge platform, developed within Annex 74. Due to a lack of harmonized data collection in past competitions large efforts were needed. A journal paper was published in the November 21 issue of the Energy and Buildings journal based on this material [voss 2021]. A systematic data collection approach was developed for the next SDE to inspire past competition data analysis.

The analysis of the energy systems has been mainly limited to the houses’ energy consumption and the energy yield of the solar power systems. The results are not comparable to standard building practise due to the difference in operation of the houses and the short period with available monitoring data.

The considerable time and expense that go into developing and constructing the buildings raises the question of an advanced monitoring concept for subsystems such as the heat pumps, the thermal solar systems and the ventilation systems. SDE 2014 had already introduced a systematic breakdown on the consumption side. In SDE 21, detailed measurements for photovoltaics are also to be added (performance ratio). There will, for the first time, also be a comparison of simulation and measurement on three trial days before the actual competition (performance gap). This will establish what findings can be obtained given the effort and investment involved.

In many areas, SDE has identified and identifies innovations in the field of energy systems for which a detailed quantitative assessment has not yet been possible within the framework of the competition. It remains the role of the teams to pursue these questions after the competition by working on their houses at their permanent locations. Many teams have done so in the past, operating the buildings as living labs at their universities. At SDE 2019, at SD Africa in Morocco 2019 and indeed in Dubai at SDME 2018, some buildings were for the first time able to remain on the competition site, as the competition sites were part of research centres. This has benefits for subsequent research. In the case of SDE 2019 and SDME 2018, it had a very negative impact on visitor numbers. It remains to be seen what research will be done with the houses at these sites. The potential for scientific work is certainly there. Another advantage of buildings remaining on the site is that it allows systematic commissioning and adjustment to achieve improved results in subsequent measurements. For buildings that remain in place, systematic, scientific tests can be carried out at building level (co-heating tests) and at component level (dynamic U-value testing, COP analysis,... [iea ebc annex 71]). As a rule, however, the buildings then remain uninhabited, as living on test sites is not permitted under local building regulations.

Considering the number of limitations for energy systems and research given by the fact of a common event site, a decentral competition throughout Europe might be an option for further investigations. It allows to keep the triple of “design-build-operate” but widen the scope of possible energy engineering with respect to the given sites. An example for such a concept was the Oman Eco House Competition in 2014 with five different buildings on different sites in the country [oman 2014]. The US Solar Decathlon for 2023 is also planning in that direction.

Some teams at previous SDE competitions had already decided to produce their entry in the context of a real construction task and site. The energy concept thus reflected not only the best fit with the rules of the competition, but also with that specific site and task. This is not an easy balancing act. SDE 2021 specifies further development as multi-storey residential buildings. Energy concepts for real construction tasks are to be developed. The house (demonstration unit) on the competition site represents only part of that task. A few teams in earlier competitions decided themselves to take on such challenges. SDE 2021 is, however, the first edition at which the jury will consider the energy concept for the building as a whole and not just that of the demonstration building at the competition [sde21 2019]. The focus on electricity as the sole power source no longer applies for the complete buildings. However, this criterion still holds for the demonstration buildings on the competition site.

4. Monitoring – System Design and Data

The following chapter report on the monitoring concepts applied and data available from the various editions of the Solar Decathlon. No information was made available for the Latin American editions and for SDE 2019.

4.1 Solar Decathlon US[16]

This chapter contains an overview of the monitoring applied in the U.S. editions of the Solar Decathlon.

4.1.1 SDUS 2002-2017

In short, the data collected for the Solar Decathlon can be categorized as “task completion” and “measured performance”. Task completion may involve activities such as washing a load of laundry or hosting a dinner party and have varied over the editions to align with current interests by students, researchers, and best practices. For the most part, the tasks are approximations of what a homeowner might expect their home to perform reliably and serve as a baseline for a fair competition. The measurement is not intended to be perfectly accurate or the best possible way of determining the performance of the task but rather to ensure that teams could complete the task while on a temporary construction site and that measurements would be equally collected for all competing teams. Additionally, due to shipping issues, student errors, or strategies unique to the competition such as earning a 1st place in the energy contest by sacrificing performance in another contest such as appliances to save energy, the measurements should not be construed as the actual performance of the house, but rather, the performance of the team in the competition. When comparing the results for these task-completion contests, one should focus on the types of tasks being completed and its relative importance vs. how a house performed in the contest as compared to a standard, occupied house in the market.

Since the monitoring data in all competitions were used for the scoring of energy and comfort related contests, aspects such as calibration and error detection are important for a fair evaluation. Unfortunately, because each competition occurs under a different climatic condition and for only several days, during which the house is subject to non-typical operational capabilities, there is limited further research possible from the actual temperature, humidity, or energy use data. It can be insightful for how one team or technology compared against another in a particular competition edition, but measurements across competitions is likely not practical.

Primarily, the source of information for this subchapter were the Rules documents for each competition. Electric energy consumption and generation are documented in one-minute intervals; whereas measurements related to comfort aspects and appliances are available in both one-minute resolution and as 15-minute averages. 15-minute averages were used so as to minimize the effect of a short period of time during which a person was standing over a sensor or a refrigerator door was open that unluckily happened to coincide with the moment the measurement was collected. Regardless of competition year, for the U.S. competition editions, all sensors were connected to a Campbell Scientific CR-1000 or similar data logger. In some years, a wired connection was used; in other years, a wireless connection was achieved. The monitoring was executed by the National Renewable Energy Laboratory (NREL).

In most competition years, in order to evaluate indoor comfort aspects, the temperature, humidity, air quality and illumination were measured and recorded.

To record temperature, a minimum of two and a maximum of four locations were identified in each home that would be representative of the performance of the space. This would be a space that was not in the

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[16] Author: Josef Simon, NREL, USA

direct path of supply air flow, not in direct sunlight, and not adjacent to a thermostat. It would also be a location where occupants would likely spend a significant amount of time. In each of these locations, a tripod with a temperature sensor was placed. In early years, active ventilated type k thermocouple sensors with a +-0.5% calibration were used. In later years, after evidence showed that since the sensors were not placed in direct sunlight, active ventilation was not appropriate, standard temperature sensors were used. Throughout each competition, the measurement that deviated most from the target temperature for the Rules was that which was used for scoring. It is important to note that outside of the scored periods, unique to each competition, teams were not expected to condition their homes and, often, thousands of visitors through the home made it impossible to do so. As such, one should not review the full temperature profile of the house over the period of the competition and consider it to be indicative of the way in which that house would perform under normal residential conditions.

Humidity was evaluated in much the same way, with the exception being that only one sensor was used per conditioned envelope.

For some competition cycles, interior air quality was evaluated by proxy through use of a CO_2 sensor. Teams earned full points for keeping the CO_2 levels below 1,000 ppm on average during scored periods. Only one CO_2 sensor was used per team and at least 2 of the measurement periods were done while the house was occupied for the Dinner Party contest. It is important to note that teams were able to monitor the measurements collected by the organizers in real time and had the option to manually open windows or doors in the house to adjust the CO_2 level such that performance should not be indicative of the automatic performance of the house, but rather the performance of the team and its house for the duration of the competition.

In early years of the Solar Decathlon U.S. competition, illumination at the work place was measured by a photometric sensor. We saw, however, that teams would simply place a low-watt LED light that met the required lighting condition at the minimum-allowable height over the work surface to earn points with minimal energy expenditure. In later years of the competition, the organizers used two REED handheld light level sensors with on-board data logging capabilities to record the average illumination during the scored period of two rooms in each house, typically the living or dining space and the main bedroom. Similar to temperature and humidity, the sensor was placed on a tripod and mounted approximately 3 feet off the ground at a location where the occupants would need sufficient lighting for comfort and typical household activities.

The scoring of the appliance sub contests was primary based on operation and not active or time-series measurements. For example, teams would be required to boil a certain quantity of water within a certain period of time, using energy, testing the functionality of the appliance, and placing humidity into the environment that was simultaneously evaluated by the Humidity sub contest. Other appliances included running the dishwasher, washing and drying towels, and operating a refrigerator and freezer. As the students in the competition typically did not design or build these appliances, the goal of the measurements was not to evaluate how efficient or effective the appliance itself was, but rather to confirm that the house had the ability to function adequately for a theoretical homeowner. As such, most of the appliance activities fell into task-completion categories.

Electrical energy generation, consumption and optional storage were measured using utility grade meters. Additionally, a bidirectional one measured electricity generation and consumption of the inverters. In certain years, teams earned points for excess power generation, in other years, teams earned points for consuming less than a fixed amount of energy over the course of the competition, designed based on the tasks a team was expected to complete. As teams were not required to complete all tasks, however, the total consumption may not actually represent an equal amount of work done by each house but rather what tasks a team chose to complete. For example, a team that had earning full points in Energy Balance as a priority might choose a solar hot water heater to avoid electric hot water heating demand or may choose to earn 0 points in dishwashing to minimize energy consumption. In the U.S. edition of the competition, this type of strategizing was encouraged.

Data for all temperature, humidity, energy consumption, energy production, refrigerator temperature, freezer temperature, interior lighting, and task completion activities are available for every U.S. edition and for every house on the competition portal. It is important to remember, however, that the data is only relevant in the context of earning points for the competition, it should not be indicative of the house performance itself under normal operating conditions.

Data from the SD US editions 2011/13/15/17 have been transferred to the knowledge platform. All data are in harmonized tables. Only the data from 2013 upwards include weather data such as outdoor temperature, humidity and irradiation as well as energy consumption and generation. Energy data for the 2011 competition are limited to import and export on the interface to the grid.

The equipment used for each edition were typically as follows, with minor modifications or improvements from year-to-year for improved technology such as wireless communications or ability to run without a constant power source.

The locations of sensors were planned in advance through negotiations between the organizers and each team. Installation had to be completed before the start of the objectively measured contests. Most of the teams, despite their best intentions, often finish construction of their houses during the time intended for assembly or setup, which makes installation of instrumentation a bit tricky. Before active scoring began, the instrumentation team had to allow time to verify correct functioning of the monitoring systems and to correct any problems with the systems.

- Lighting levels

  Instrument: Photometer, photovoltaic type with filter
  Source: Licor, Inc., model LI-210 photometric
  Accuracy: 5% of reading
  Location: Home office workstation for some years, living space for later years

- Indoor temperature and relative humidity (RH)

  Instrument: RTD, variable capacitance RH, linear DC output.
  Source: Vaisala, Inc., model Humitter. PointSix sensor in later years.
  Accuracy: 0.7°F (0.4°C) temperature, 3% RH
  Location: In radiation shield in conditioned zone, 1.2 m to 1.5 m above floor level

- Temperature

  Instrument: Type-T thermocouple, special limits of error
  Source: Omega Engineering, Inc., part number TT-T-24S-TWSH
  Accuracy: About 0.5°C
  Locations: In radiation shield in conditioned zone, 1.2 m to 1.5 m above floor level; inside refrigerator and freezer, immersed in glycol solution; inside insulated container for shower tests

- AC electricity

  Contest: Net Metering Instrument: Utility grade meter
  Source: GE kV2c Encompass meter
  Accuracy: 0. 5%
  Location: In a meter housing mounted on the house or on a free-standing structure on the team's lot

For the 2017 and future editions, data collected were updated in near real-time to the Solar Decathlon website so that students and the public could personally view the performance of each house. The interactive web-based interface provided extensive visibility for educational purposes.

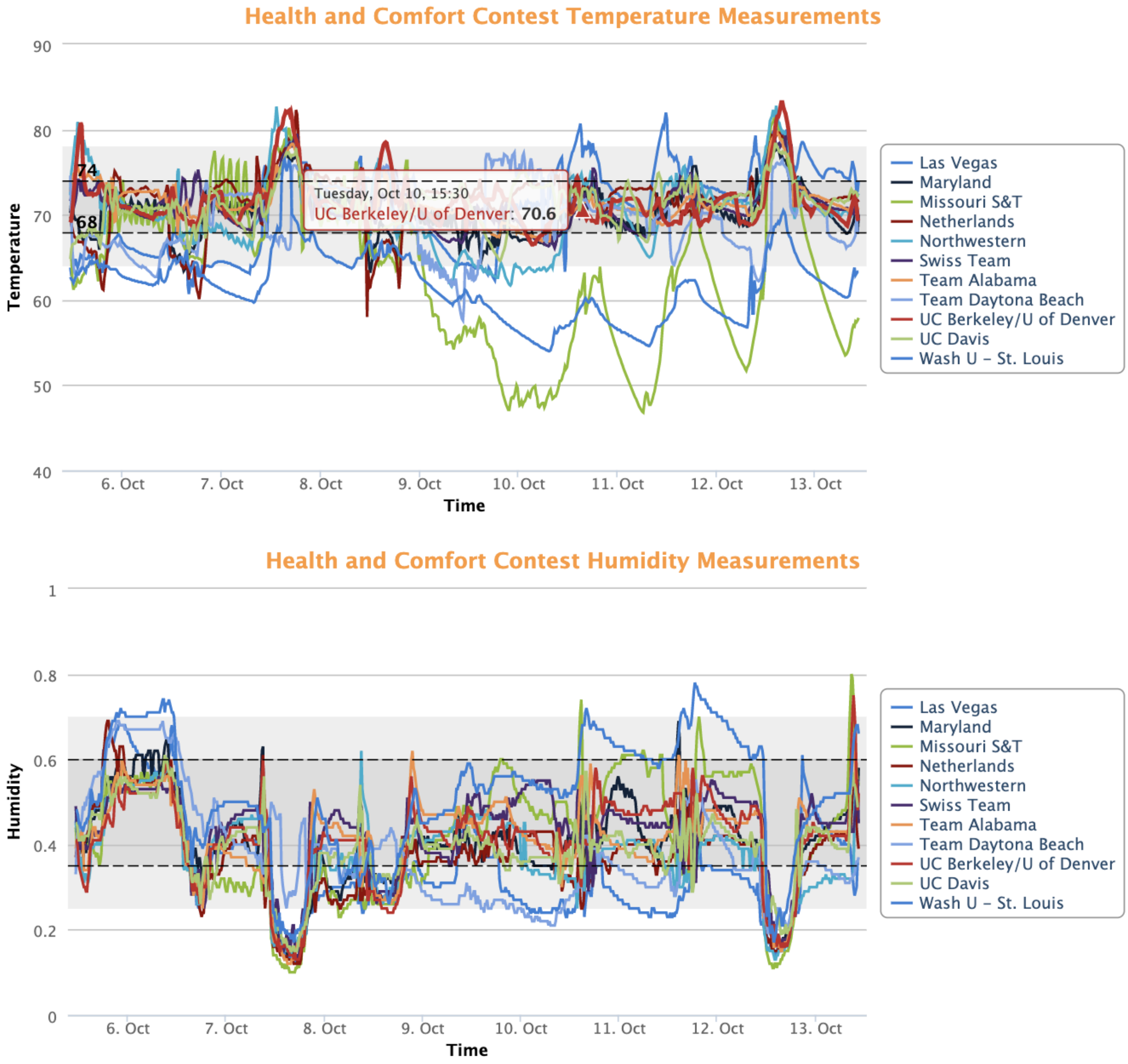

Figure 145: Example of Data Display from U.S. SD 2017, Source: U.S. Department of Energy Solar Decathlon Organization

In prior years, data were made available through an extensive spreadsheet that consumed information collected by data loggers and sensors located in each home.
Summarizing the measured data available for each competition cycle can be simplified as follows. Note that this summary table does not characterize the task-completion contests, such as running a certain number of clothes washer loads or similar where points were simply earned for demonstrating functionality, though this data is available at www.solardecathlon.gov .

Table 11: Table With Overview Of Data Points Per Competition, Source: U.S. Department of Energy Solar Decathlon Organization

	2002	2005	2007	2009	2011	2013	2015	2017	2020
Indoor Temperature in 15-min increments (Typically 2 – 4 measuring points per building)	X	X	X	X	X	X	X	X	X
Indoor Humidity In 15-min increments (Typically 1-2 measuring points per building)	X	X	X	X	X	X	X	X	X
Indoor Air Quality (CO2 Levels) (1 measuring point per building)							X	x	X
Lighting Levels at Desk Workstation (1 measuring point per building)	X	X	x	X					
Lighting Levels in Main Living Spaces (2 measuring points per building)								X	x
Exterior Noise Infiltration (2 measuring points per building)									x
Interior Noise Generation (2 measuring points per building)									x
Electric Vehicle Usage (Multiple tasks per year, varies)	X	X	X	X		X	X	X	x
Energy Production Over Time (Evaluated over a 9-day period)			X	X	X	X	X	X	
Energy Consumption Over Time (Evaluated over a 9-day period)	X	X	X	X	X	X	X	x	
Time-Value of Energy (Evaluated over a 9-day period)								X	
Refrigerator Performance (Evaluated for 9 days, 15-minute averages of data collected every 1 minute)	X	X	X	X	X	X	X	X	X
Freezer Performance (Evaluated for 9 days, 15-minute averages of data collected every 1 minute)	X	X	X	X	X	X	X	X	X

4.1.2 SDUS 2020

Beginning with the 2020 edition of the competition, to reduce the carbon footprint of the competition associated with transporting house modules to a central competition site as well as the cost borne by the teams and organizers to enable such an activity, efforts were made to enable a “local build” Solar Decathlon wherein each house would be evaluated in its own region or area as built permanently. In this way the performance of the house could be evaluated within the weather conditions that aligned with the design of the home. Given cost constraints and the need to evaluate each house in a limited number of days, in either a remote-site location or on a temporary event location, the measurement system design for the 2020 edition of the U.S. Solar Decathlon is primarily focused on functionality validation vs. long-term collection of house performance data. Should there be an interest in evaluating the longer-term performance of each house for research purposes, some minor changes to the monitoring approach could be made, which are explained in more detail within this section.

As a prerequisite, all competing teams were required to install full branch-circuit level monitoring equipment within their competition prototype. Additionally, the utility-grade CTs and E-gauge energy monitoring equipment is provided free-of-charge to each team for long term installation and monitoring of whole-home energy consumption and energy production. All data is available via the web for review by teams and organizers.

Additionally, recognizing that interconnection with local utilities including PV generation can sometimes be significantly delayed, so as to minimize risk to the ability to collect competition measurements, each house was required to install an electric energy battery storage system and design their home to be able to operate off-grid.

Once all this was in place, the contests evaluated by calculations, in some form, are summarized as follows:

Table 12: Contest evaluation procedure, Source: U.S. Department of Energy Solar Decathlon Organization

Sub Contest Name	Short description	Tool
Energy Efficiency	HERS Score Without PV	Energy Rater
Energy Production	Ability to produce power w/ PV	E-Gauge Energy Meter
Net-Zero Energy	Estimated annual production minus consumption	Energy Modeler
Demand Response	Capability to shed 30% of peak load automatically	E-Gauge Energy Meter
Off-Grid Functionality	Ability to maintain critical loads	E-Gauge Energy Meter + Battery Specifications
Kitchen Appliances	Ability to operate all kitchen appliances	Observer + temperature sensor
Hot Water	Number of millilitres of water drawn before hot water is achieved	Observer + graduated cylinder
Laundry	Ability to wash clothes using an automatic clothes washer	Observer
Electric Lighting	Ability to maintain acceptable indoor light levels at night	Light level meter - handheld
Home Electronics	Smart outlets, circuit-level data monitoring, and functional equipment	Observer
House Occupancy	Host a dinner party using the house features	Observer
Electric Vehicle Charging	Fully charge an electric vehicle using house infrastructure	Observer
Temperature Control	Maintain interior temperature within an acceptable band.	HOBO Battery-powered sensor
Humidity Control	Maintain interior humidity within an acceptable band.	HOBO Battery-powered sensor
Indoor Air Quality	Keep interior CO2 levels below unsafe levels.	HOBO Battery-powered sensor
Air Tightness	Demonstrate an air-tight house.	Blower Door Test
Exterior Noise Infiltration	Demonstrate minimal infiltration of exterior noise to the interior living space	Sound meter + calibrated speaker
Internally Generated Noise	Demonstrate a comfortable internally generated noise for occupants.	Sound meter + calibrated speaker

As the first edition of the competition using this process is still underway, delayed due to COVID-19, measurements are not available at the time of publication. The important note here, from a research point of view, is that the tasks were designed to demonstrate a minimum level of functionality in each home for a homeowner and which should be met in every climate condition a home might face. For fairness, we could not evaluate total energy consumed or performance over time as each home is located in a different climate zone and as an international competition, some are experiencing winter during the testing period while others are experiencing summer.

To enable longer-term monitoring and research, however a Campbell Scientific CR-1000 or similar data logger with a cell-modem and power connection along with wired sensors could provide long-term information about the house. How each home is occupied or operated, however, would have notable impacts on the data collected.

4.2 Solar Decathlon Europe[17]

This sub chapter contains an overview of the monitoring applied in the European Solar Decathlons 2010/12 Madrid and 2014 Versailles. For 2019 in Szentendre no information is available. Since the monitoring data in all competitions were used for the scoring of energy and comfort related contests as well as for energy use of household appliances, aspects such as calibration and error detection are important for a fair evaluation. Detailed documentation of monitoring hardware and methods lay the foundation to compare measuring data of different SD competitions. Furthermore, it enables additional research. Table 13 gives an overview on available data resolution and periods for the competitions described in the following sub chapters. A graphical visualization is part of a separate focus report. Each SDE is represented in a separate subchapter. First, the available monitoring data are clustered and afterwards specifications of devices and sensors as well as the measurement resolution are described.

Table 13: Overview on available periods and data resolution for the competitions described in the following sub chapters. All data are downloadable from the knowledge platform after login: www.building-competition.org A graphical visualization is part of a separate focus report .

	SDE	measuring points per building	scored period / possible interval for tasks	Time resol.
Insolation	10 Madrid	-	-	-
	12 Madrid	-	-	-
	14 Versailles	1	Monday…Sunday: 00…24:00	1 min
Ambient air temperature	10 Madrid	-	-	-
	12 Madrid	-	-	-
	14 Versailles	1	Monday…Sunday: 00…24:00	1 min
Relative ambient air humidity	10 Madrid	-	-	-
	12 Madrid	-	-	-
	14 Versailles	1	Monday…Sunday: 00…24:00	1 min
Interior air temperature	10 Madrid	2	Wednesday…Monday: 00…11:00 / 14…18 / 23…24:00 | Tuesday 00…24:00	1 min
	12 Madrid	2	Monday…Friday: 00…06:00 / 10…16:00 / 21…24:00 Saturday & Sunday: 00…06:00 / 23…24:00	15 min
	14 Versailles	3	Monday…Friday: 00…11:30 / 15…17:30 / 20…24:00 Saturday & Sunday: 00…08:00 / 23…24:00	1 min
Relative interior humidity	10 Madrid	1	Wednesday…Monday: 00…11:00 / 14…18 / 23…24:00 | Tuesday: 00…24:00	1 min
	12 Madrid	1	Monday…Friday: 00…06:00 / 10…16:00 / 21…24:00 Saturday & Sunday: 00…06:00 / 23…24:00	15 min
	14 Versailles	1	Monday…Friday: 00…11:30 / 15…17:30 / 20…24:00 Saturday & Sunday: 00…08:00 / 23…24:00	1 min
Air quality CO_2	10 Madrid	1	Wednesday…Monday: 00…11:00 / 14…18 / 23…24:00 | Tuesday: 00…24:00	1 min
	12 Madrid	1	Monday…Friday: 00…06:00 / 10…16:00 / 21…24:00 Saturday & Sunday: 00…06:00 / 23…24:00	15 min

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[17] Author: Moritz Stark, University Wuppertal

	SDE	measuring points per building	scored period / possible interval for tasks	Time resol.
	14 Versailles	1	Monday…Friday: 00…11:30 / 15…17:30 / 20…24:00 Saturday & Sunday: 00…08:00 / 23…24:00	1 min
Lighting Level	10 Madrid	1	Friday…Monday, Wednesday: 08…11:00 / 21…23:00 | Tuesday, Thursday, Friday: 8...11:00	1 min
	12 Madrid	1	Monday…Wednesday: 08…10:00 / 14…16:00 / 21…23:00 Thursday & Friday: 08…10 / 14…16:00	15 min
	14 Versailles	-	-	-
Acoustic performance	10 Madrid	1	during assembly	value
	12 Madrid	1	during assembly	value
	14 Versailles	-	-	-
Temperature of Fridge & Freezer	10 Madrid	one each	Monday…Sunday: 00…24:00	1 min
	12 Madrid	one each	Monday…Sunday: 00…24:00	15 min
	14 Versailles	one each	Monday…Sunday: 00…24:00	1 min
Temperature of other Appliances	10 Madrid	one each	Cloth washing, dishwasher, oven: Friday: 08…11:00 / 13…17:00 / 20…22:00 Saturday: 08…11:00 / 14…17:00 / 21…22:00 Sunday: 08…11:00 / 14…17:00 / 19…22:00 Monday: 08…11:00 / 13…18:00 / 21…22:00 Tuesday, Wednesday, Thursday: 08…21:00	1 min
	12 Madrid	one each	Cloth washing, dishwasher, oven: Monday…Thursday: 08…16:00 / 20…23:00 Friday: 08…16:00	15 min
	14 Versailles	one each	**cloth washing:** Monday…Friday 08…11:30 / 14:30…17:30 / 19:30…23:00 **dishwasher**: Monday, Wednesday…Friday 08…11:30 / 14:30…17:30 / 19:30…23:00 **oven**: Monday…Thursday 14:30…17:30 / 19:30…23:00	1 min
Electrical energy generation	10 Madrid	1	Monday…Sunday: 00…24:00	5 min
	12 Madrid	1	Monday…Sunday: 00…24:00	15 min
	14 Versailles	1	Monday…Sunday: 00…24:00	1 min
Electrical energy consumption	10 Madrid	1 + 1	Monday…Sunday: 00…24:00	5 min
	12 Madrid	1 + 1	Monday…Sunday: 00…24:00	15 min
	14 Versailles	1 + 2	Monday…Sunday: 00…24:00	1 min
Battery	10 Madrid	-	no separate data point	-
	12 Madrid	1	Monday…Sunday: 00…24:00	15 min
	14 Versailles	1	Monday…Sunday: 00…24:00	1 min

4.2.1 SDE 2010

The main source of information used to create this subchapter was taken from the former rules document and a monitoring summary report [upm 2010] [upm 2009]. Electric energy consumption and generation are documented in five-minute intervals; whereas measurements related to comfort aspects and appliances are available in one minute resolution. All sensors were attached to an I-Lon smart server from Echelon by a wired connection, which was used as data logger. No further documentation is available. The monitoring was executed by Seresco. Sereso is a Spanish company dedicated to the development of software solutions and the provision of services within the field of Information and Communication Technologies (ICT)[18]. The acoustic test and measurements were perfomed by ArquiLAV, Laboratorio de Acústica y Vibraciones aplicadas a la Edificación, al Medio Ambiente y al Urbanismo at UPM[19].

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[18] https://seresco.es/
[19] http://www.arquilav.aq.upm.es/

A real-time distributed monitoring system was installed in every house for its continuous supervision. The monitoring system was based on an ad-hoc designed embedded system connected through an RS-485 serial bus to several distributed nodes and power meters. The nodes were running a real-time operating system which took care of acquiring all measurements at specific time frames. Every 10 ms, each node obtained information from all the sensors to which it was connected. Every second, the monitoring node performed the mean of the last 100 measurements and stored it internally to be acquired by the main controller through an RS-485 RTU-Modbus protocol. The meters were commercial meters with an RS-485 RTU-Modbus protocol.

The main controller was based on an embedded Linux operating system. It was made of a microcontroller with a UPS system and an electronic carrier to connect to the nodes. Every minute, the main controller acquired all measurements stored on the nodes and meters and accumulated them on an internal SD card. This information was stored together with the date and time. Moreover, every minute the main controller sent the data stored to the monitoring server. The monitoring server was in charge of synchronizing all data, performing all conversions from electrical to physical measurements and running periodic scripts which processed the data, made the points calculations and uploaded them to the monitoring database. Finally, all information was shown on a real time monitoring website.

In order to evaluate indoor comfort aspects, temperature, humidity, air quality and illumination were measured and recorded. In the main room of the demonstrators, a tripod with a temperature, humidity and CO_2 sensor was placed. To evaluate the interior air temperature an additional sensor was located in the bedroom and if necessary, a third one in another room. Active ventilated type k thermocouple sensors with a +-0.5% calibration were used. To obtain ambient values, a HT/O sensor from Trend was used. It contained a capacitive sensor with an accuracy of +-2% to measure relative humidity and a current sensor as well as a thermistor for the temperature. Although the equipment was described, no measured values are available.

The interior air quality was evaluated by a GMW115 carbon dioxide transmitter from Vaisala, which had an accuracy of +-2%. The illumination at the work place was measured by a LI-210SA photometric sensor from LI-COR, which contained a filtered silicon photodiode. During assembly phase, the airborne sound insulation of a facade from each team was measured with an analyser (type 2260), calibrator (model 4231) and an acoustic source (4224) from Brüel & Kjær. The evaluation was according to ISO 717-1:1996 [acu 2010].

The scoring of the appliance sub contests was primary based on operation temperature measurements. Type k thermocouples with a calibration of +-0.5% were used for this reason. Another task for the teams was to run home electronic devices during defined time intervals. In order to verify an uninterrupted operation, all devices were connected to a separate electrical circuit and the consumption was measured by a CONTAX 2511 electricity meter from Orbis with a S0 interface (see Figure 146, meter number four).

Electrical energy generation, consumption and optional storage were measured by Domotax meters from Orbis with a 0.25 Wh resolution. A bidirectional one measured electricity generation and consumption of the inverters. If energy from a battery was used to cover demand, an additional 20% of the drawn energy was manually added to the consumption data.

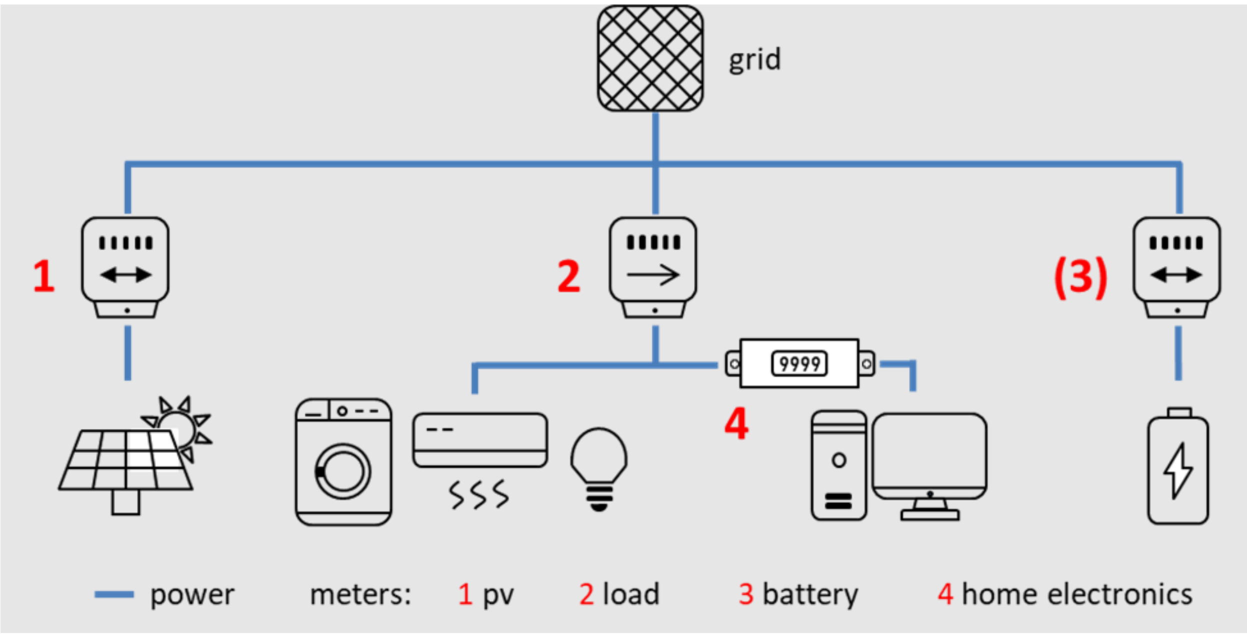

Figure 146: Principle sketch of electrical energy measurement SDE 2010 and SDE2012, source: University Wuppertal

4.2.2 SDE 2012

Information and descriptions on the sensors used in the SDE 2012 were obtained from the document “Monitoring Procedures Information for Teams” [upm 2012]. Available measurement data are visualized in the sub report 1. The hardware design and software development was performed by Álvaro Gutiérrez Martín, Associate Professor of Automatic and Control Systems at Universidad Politécnica de Madrid (UPM)[20]. As well as in 2010, the acoustic monitoring was executed by the laboratory ArquiLAV of UPM. Measurements can be categorized into three sections:

1. indoor comfort
2. temperatures of household appliances
3. electrical energy performance

Values with a resolution of 15 minutes are available for all three categories. Except for electricity generation, the measurements are continuously documented over the entire competition. Data related to the sub contests cloth dryer, home electronics, cooking and hot water draws have not been made available. Continuous measurements from category one and two were collected by a Twido PLC (TWDLCDE40DRF) from Schneider Electric and send to an individually designed TJ Monitor, which is based on a SAM9G20 module from RBZ Robot Design. These devices sent all data to the monitoring server (see Figure 147).

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[20] http://www.robolabo.etsit.upm.es/aguti/index.html

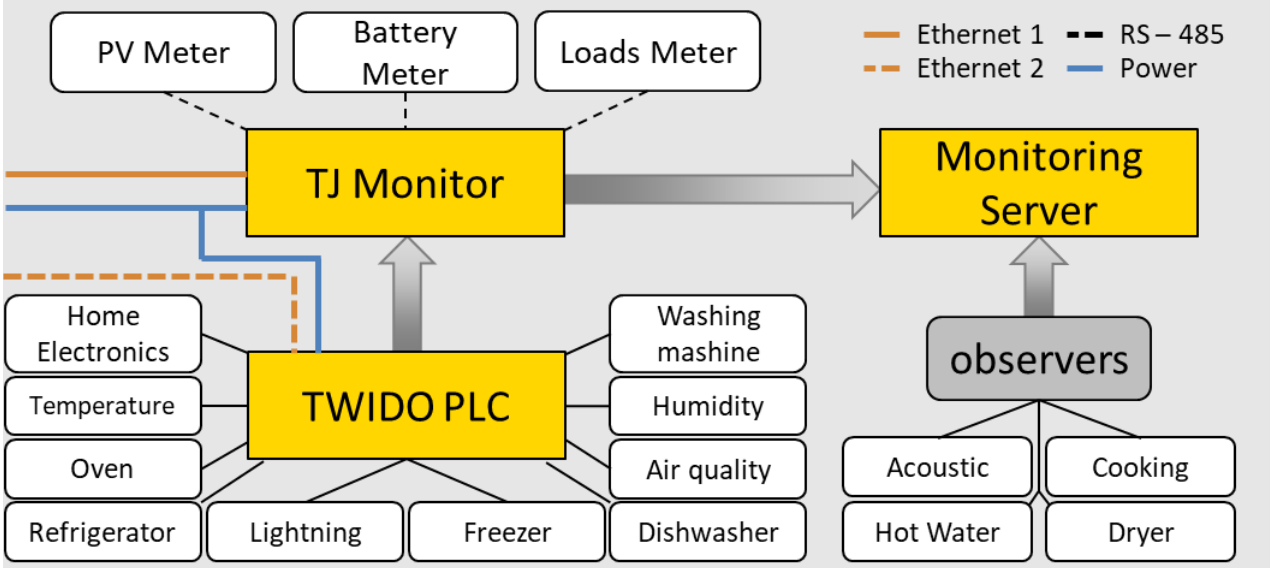

Figure 147: overview of the monitoring system SDE 2012, Source: University Wuppertal

The comfort category contains interior air temperature, relative humidity and illumination measurements. Mounted on a tripod in the living room, a Schneider SCR110-H Sensor recorded air temperature, relative humidity and air quality. The CO_2 sensor was a non-dispersive infrared (NDIR) one and the temperature / humidity sensor used a Vista 1.8K negative temperature coefficient thermistor. In a second room, e.g. the bedroom, only temperature was obtained by a STR100 Sensor from Schneider Electric. The interior illumination was measured with a Space Light Level Sensor (LLS) from Trend and a range from 0 to 8000 lx was selected. The airborne sound insulation of a facade from each team was measured with an analyser (type 2260), calibrator (model 4231) and an acoustic source (4224) from Brüel & Kjær during assembly phase [acu 2012].

During the operation of household appliances, operation temperatures were measured with a type K or T thermocouple, which were suited for a temperature range from -75°C … +250°C. In the home electronics contest, devices had to be operated during defined periods. In order to check this, devices needed to be connected to a separate electrical circuit and the energy consumption was measured by an EN40P electricity meter from Schneider Electric. It had an S0-Interface and a 10 Wh resolution (see Figure 146, electricity meter number four).

The third category contains power generation, consumption and battery storage. For measurement at least two Domotax AC electricity meters with a 0.25 Wh resolution from Orbis were used. If a battery was used, an additional electricity meter was inserted, Figure 146. Note that the photovoltaic electricity meter is bidirectional in order to record the energy consumption of supply and feed-in.

4.2.3 SDE 2014

The primary resource of information for this subchapter was the “Solar Decathlon Europe 2014, monitoring procedure” document [cstb 2014]. The hardware design was developed as in SDE 2012 by Álvaro Gutiérrez Martín, Associate Professor of Automatic and Control Systems at Universidad Politécnica de Madrid. The software development came from NOBATEK/INEF4[21].

In contrast to 2010 ambient temperature, humidity and insolation were also measured. Due to the lack of detailed documentation, e.g. the sensor models used, no further summary could be written. Nonetheless, the data are visualized in sub report 1. The monitoring system had an updated version of the TJ monitor from the SD 2012, see Figure 148. The devices related to the Twido PLC were replaced by an analogue module, a thermocouple module and a PT100 module from rbz. The measured data have a one-minute resolution. No information is documented on the organization performing the monitoring.

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[21] https://www.nobatek.inef4.com/en/

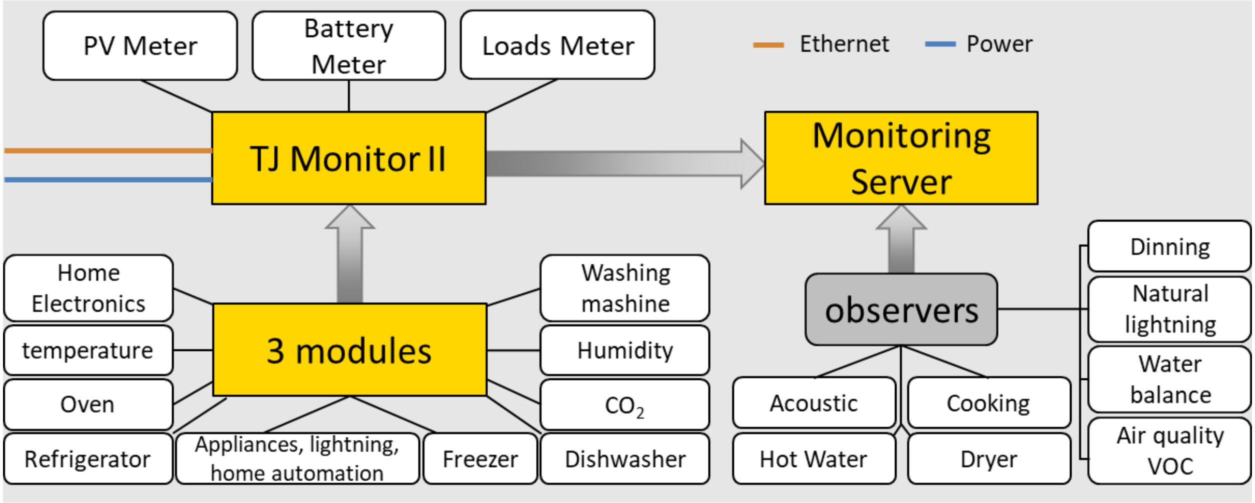

Figure 148: Overview monitoring system SDE 2014, Source: University Wuppertal

Similar to the SDE 2010, interior air temperature, humidity and air quality were measured to evaluate comfort aspects. PT100 temperature sensors were enclosed in a 40 mm black globe and used in the living room, bedroom and in a third room in dependency of the individual house configuration. They were four-wired connected, according to the NF EN 60751 standard, and met the requirements for a 1/10 tolerance class. The relative humidity and air quality (CO_2) were measured in the main room with an SCR110H Sensor from Schneider Electric, which also contains a temperature sensor. The humidity sensor is based on a thin-film capacitor and the CO_2 sensor is a nondispersive infrared one. For each day during the competition a maximum and two minimum temperatures (00:00…08:00 | 08:00…24:00) were set. In order to achieve points in the temperature contest, teams needed to adapt the interior air temperature according to the ambient one. The following Figure 149 illustrates the relationships.

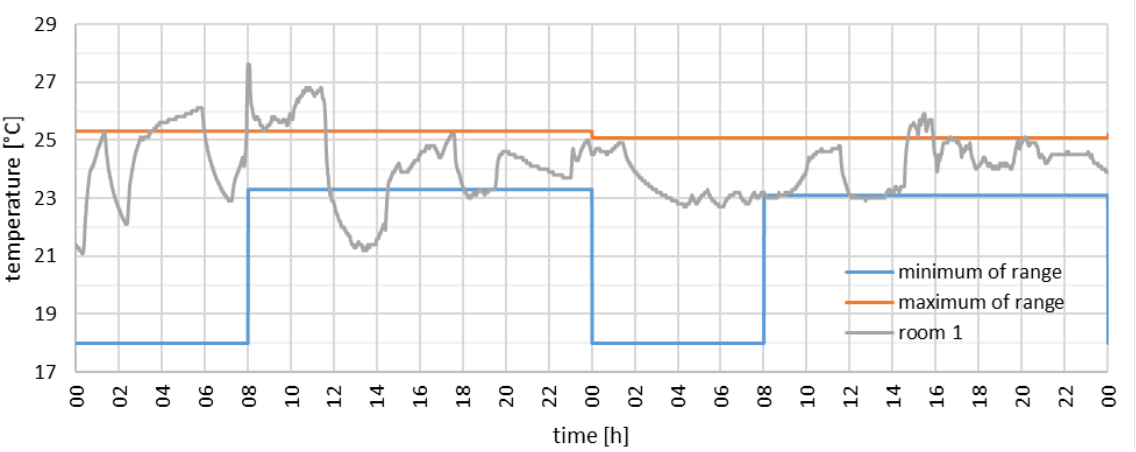

Figure 149: Exemplary course of an individual temperature range for scoring (two competition days), Source: University Wuppertal

The measurements of temperatures during the operation of appliances are in a second category. A type T thermocouple with a temperature range from -10°C to +300°C was used in the fridge, freezer, washing machine, dishwasher and oven.
Generation, consumption and storage form the third category were measured with up to three A9MEM3155 3-phase electricity meters from Schneider Electric with a resolution of 1 Wh. A detailed overview is given in Figure 150. The electric energy consumption of appliances and home electronics was separately measured

due to scoring aspects. Therefore, two additional Schneider energy meters (EN40P) were installed in each house.

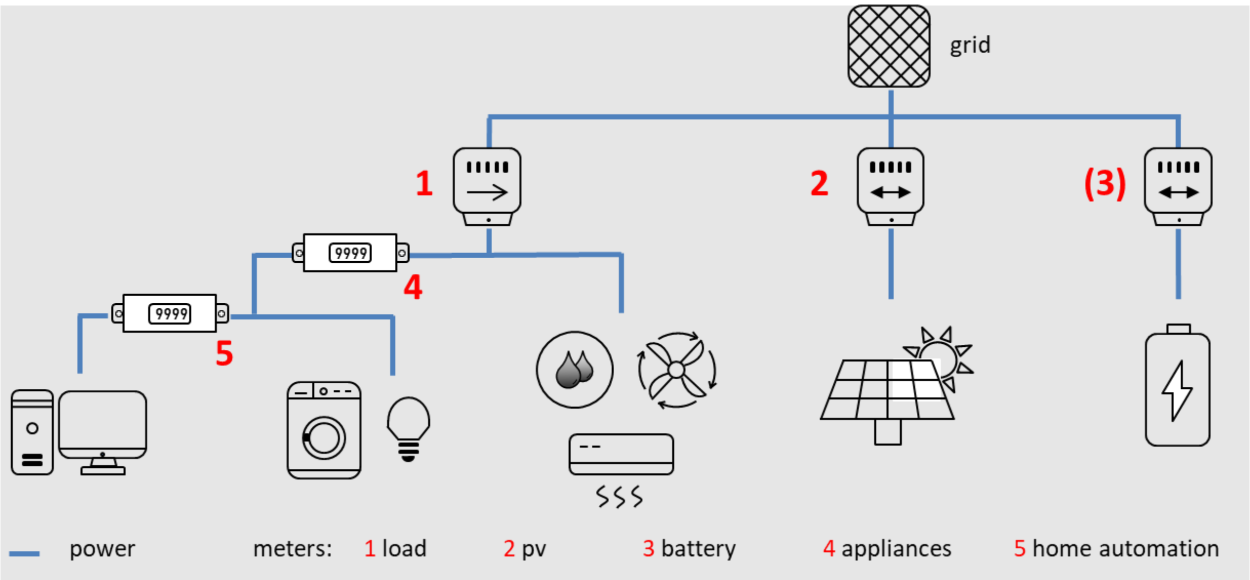

Figure 150: Principle sketch of energy measurement SDE 2014, Source: University Wuppertal

4.3 Solar Decathlon Middle East[22]

The monitoring applied in the first Middle East version of the Solar Decathlon is described in this chapter. Basis for this summary was the “Solar Decathlon Middle East, Technical Monitoring Procedures” document and direct information from the monitoring company [dewa 2018]. The monitoring was undertaken by the TÜV Rheinland Consulting GmbH. As before, the monitoring data are clustered into three categories. In contrast to earlier SD events, not only the electricity consumption and respectively power values were documented, but also contests like demand response. The measurement data have a resolution of one minute and were obtained by wired sensors. They are visualized with a separate focus report. In selected figures, scored periods are indicated with a value of one on a secondary axis.

Table 14: Overview on available periods and data resolution for the competitions described in the following sub chapters. All data are downloadable from the knowledge platform after login: www.building-competition.org. A graphical visualization is part of sub report 1.

	SD	measuring points per building	scored period / possible interval for tasks	Time resol.
Insolation	18 Dubai	1	Monday…Sunday: 00…24:00	1 min
Ambient air temperature	18 Dubai	1	Monday…Sunday: 00…24:00	1 min
Relative ambient air humidity	18 Dubai	1	Monday…Sunday: 00…24:00	1 min
Interior air temperature	18 Dubai	3	Sunday…Wednesday: 00…09:00 / 12:30…24:00 Thursday…Saturday: 00…09:00 / 18:30…24:00	1 min
Relative interior humidity	18 Dubai	3	Sunday…Wednesday: 00…09:00 / 12:30…24:00 Thursday…Saturday: 00…09:00 / 18:30…24:00	1 min

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[22] Author: Moritz Stark, University Wuppertal

	SD	measuring points per building	scored period / possible interval for tasks	Time resol.
Air quality CO_2	18 Dubai	1	Sunday…Wednesday: 00…09:00 / 12:30…24:00 Thursday…Saturday: 00…09:00 / 18:30…24:00	1 min
Lighting Level	18 Dubai	2	Sunday…Wednesday: 12:30…20:00	1 min
Temperature of Fridge & Freezer	18 Dubai	one each	Monday…Sunday: 00…24:00	1 min
Temperature of Other Appliances	18 Dubai	one each	cloth-washer/-dryer: Sunday…Wednesday: 12…20:00 dishwashing: 1st week Monday…Wednesday, 2nd week Sunday…Tuesday: 12…20:00 oven: 1st week Sunday, Thursday, Wednesday, 2nd week Sunday …Thursday: 12…20:00	1 min
Electrical energy generation	18 Dubai	1	Monday…Sunday: 00…24:00	1 min
Electrical energy consumption	18 Dubai	3	Monday…Sunday: 00…24:00	1 min
Battery	18 Dubai	1	Monday…Sunday: 00…24:00	-

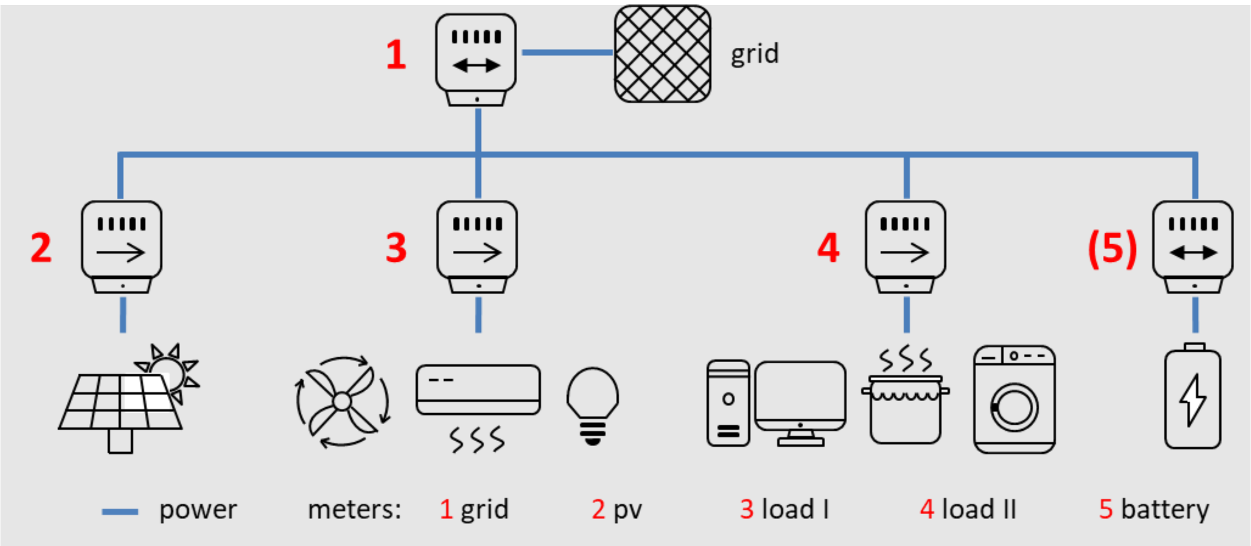

Figure 151: Principle sketch of electric energy measurement SDME 2018, Source: University Wuppertal

4.4 Solar Decathlon China[23]

4.4.1 SDC 2013

In SDC 2013, air temperature and humidity were monitored to evaluate the comfort level. A tripod with an indoor environment monitoring terminal was placed in the geometric centre of selected rooms. Indoor air quality was not considered. Temperatures of refrigerator and freezer were also monitored with temperature sensors. For the energy performance, power generation was not considered, while energy exchange between the house and the grid was measured. The measurement had a time resolution of 15 minutes. All sensors were wired and calibrated before use.

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[23] Authors: Yuan Tian, Lucas Li, Solar Decathlon China

Table 15: Overview of monitoring parameters and periods in SDC 2013

	SD	Measuring Points per Building	Scored Period	Time Resol.
Air temperature	13 Datong	3	Monday to Friday: 00:00 – 07:30 / 12:00 – 24:00 Saturday to Sunday: 00:00 – 07:30 / 16:30 – 24:00	15 min
Relative humidity	13 Datong	3	Monday to Friday: 00:00 – 07:30 / 12:00 – 24:00 Saturday to Sunday: 00:00 – 07:30 / 16:30 – 24:00	15 min
Temperature of refrigerator	13 Datong	1	Monday to Sunday: 00:00 – 24:00	15 min
Temperature of freezer	13 Datong	1	Monday to Sunday: 00:00 – 24:00	15 min
Electrical energy balance	13 Datong	1	Monday to Sunday: 00:00 – 24:00	15 min

4.4.2 SDC 2018

To evaluate the level of thermal comfort and indoor air quality, the air temperature, relative humidity, CO_2 level, and PM2.5 level were monitored. A tripod with an indoor environment monitoring terminal was placed in the geometric centre of selected rooms (ideally the living room, the bedroom, and the study room). To simulate the energy consumption for home appliances, the temperatures of the refrigerator and freezer were monitored with temperature sensors. To assess the energy system of the house, the power generation of the PV system, and the energy exchange between the house and the grid were monitored. One DC electricity meter was installed for the PV system and one (or two) AC electricity meter(s) was mounted for the energy balance. The measurement data were recorded every 15 minutes. All sensors were wireless and calibrated before use.

Table 16: Overview of monitoring parameters and periods in SDC 2018

	SD	Measuring Points per Building	Scored Period	Time Resol.
Air temperature	18 Dezhou	3	Monday to Friday: 00:00 – 08:00 / 18:00 – 24:00 Saturday to Sunday: 00:00 – 07:30 / 21:30 – 24:00	15 min
Relative humidity	18 Dezhou	3	Monday to Friday: 00:00 – 08:00 / 18:00 – 24:00 Saturday to Sunday: 00:00 – 07:30 / 21:30 – 24:00	15 min
CO2 level	18 Dezhou	3	Monday to Friday: 00:00 – 08:00 / 18:00 – 24:00 Saturday to Sunday: 00:00 – 07:30 / 21:30 – 24:00	15 min
PM2.5 Level	18 Dezhou	3	Monday to Friday: 00:00 – 08:00 / 18:00 – 24:00 Saturday to Sunday: 00:00 – 07:30 / 21:30 – 24:00	15 min
Temperature of refrigerator	18 Dezhou	1	Monday to Sunday: 00:00 – 24:00	15 min
Temperature of freezer	18 Dezhou	1	Monday to Sunday: 00:00 – 24:00	15 min
Electrical energy generation	18 Dezhou	1	Monday to Sunday: 00:00 – 24:00	15 min
Electrical energy balance	18 Dezhou	1	Monday to Sunday: 00:00 – 24:00	15 min

Depending on the configuration of the electrical system, there were two available options for the electrical meter installation. In the first case, the power generated by the PV system serves the house first, then the extra goes to the grid. A bidirectional AC meter is employed to measure the energy exchange between the house and the grid. In the alternative case, the power generated by the PV system goes directly to the grid, and the house draws electricity solely from the grid. Two unidirectional AC meters are required to determine the energy balance.

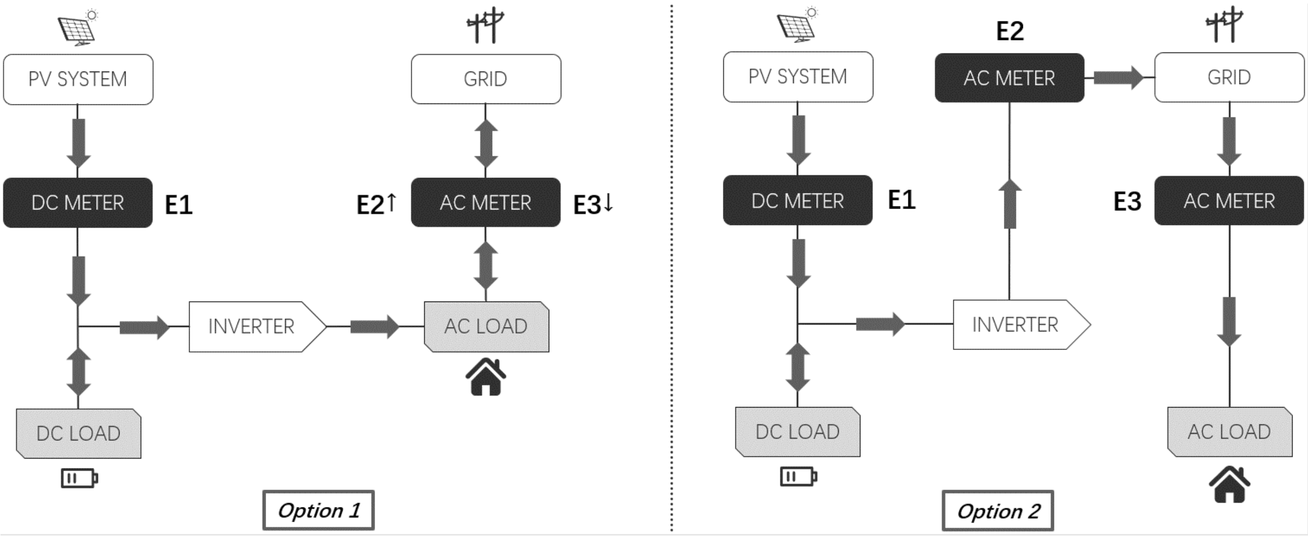

Figure 152: Schematic of energy measurement in SDC 2018

4.5 Solar Decathlon Africa[24]

In SDA 2019, the air temperature, relative humidity and lighting intensity were continuously monitored in two different places (the living room and the bedroom) in order to evaluate the thermal comfort of the participating homes, and the refrigerator and freezer temperatures were monitored with thermocouples. Also, to evaluate the houses' self-sufficient electricity provided by active solar technology, the energy production of the photovoltaic system, the charge level in the battery and the temporary Generation-Consumption Correlation were monitored. A DC electricity meter was installed for the PV system and an AC electricity meter was installed for the energy balance. The measurement data were recorded every 15 minutes during the period of monitoring. All sensors were calibrated before being used.

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[24] Author: Samir Idrissi Kaitouni, IRESEN

Table 17: Overview of monitoring parameters and periods in SD Africa. Source: Samir Idrissi Kaitouni, IRESEN

	SD	Measuring Points per Building	Scored Period From September 14th to September 25th	Time Resol.
Meteorological station	1 in the SDA site	-	Monday to Saturday: 00:00– 24:00	15 min
Air temperature	18 Benguerir	2	Monday to Saturday: 00:00– 24:00	15 min
Relative humidity	18 Benguerir	2	Monday to Saturday: 00:00– 24:00	15 min
Light intensity	18 Benguerir		Monday to Saturday: 00:00– 24:00	15 min
Temperature of refrigerator	18 Benguerir	1	Monday to Saturday: 00:00– 24:00	15 min
Temperature of freezer	18 Benguerir	1	Monday to Sunday: 00:00 – 24:00	15 min
Electrical energy balance	18 Benguerir	3	Monday to Sunday: 00:00 – 24:00	15 min

Figure 153 describes the operating principle of a local real-time monitoring system for a house. In fact, in each house, a local Monitoring system has been installed. It consists of a PLC communicating in real time with the various sensors installed in the house (temperature, humidity, light intensity, AC energy, DC energy) via an RS485 field bus (Modbus protocol).

All the measured data are systematically recorded in a database of the PLC which therefore serves also as a data logger. The measured data is displayed in real time on a touch screen. The data stored in memory is also displayed in the form of tables or graphs (curves, bar graphs, pie charts, etc.). The PLC also makes it possible to ensure the calculation of certain ratios and KPIs.

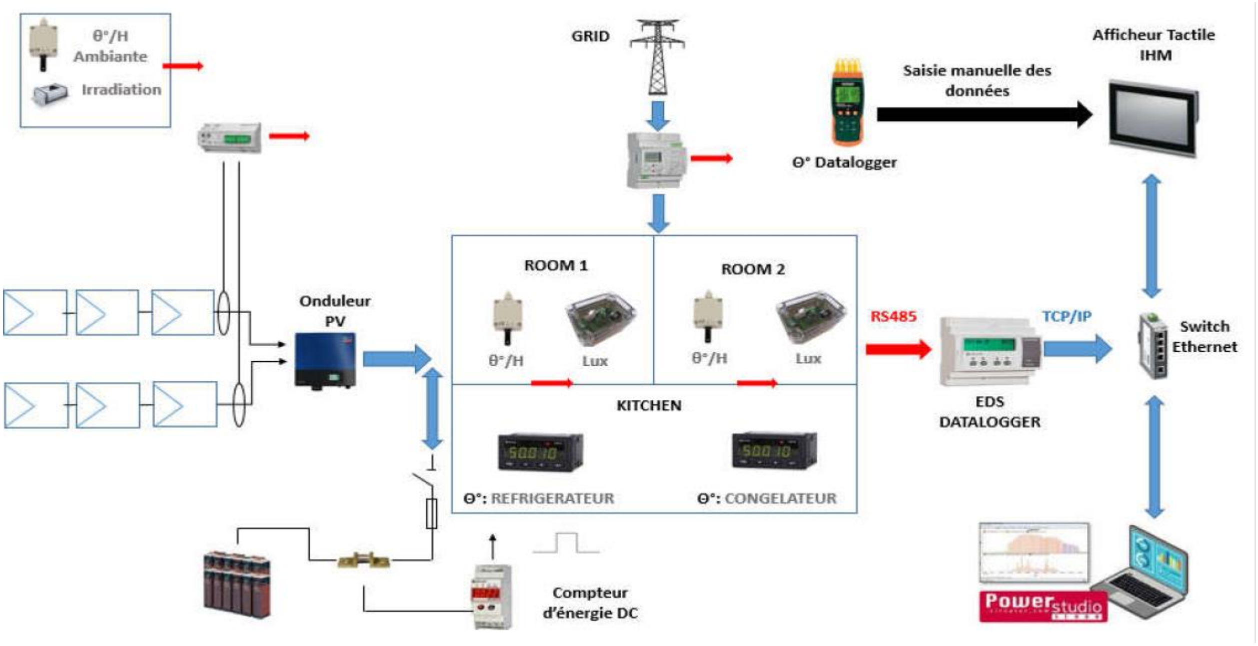

Figure 153: A synoptic diagram of the monitoring system of a house SDA, Source: Samir Idrissi Kaitouni, IRESEN

The supervision of all the houses has been done centrally in real time. One or more display screens have been installed to facilitate the display of results. The solution has been based on a server PC in which the POWER STUDIO SCADA supervision platform was installed, which centralized all the data for the competition and displayed individual and global results (statistics, averages, etc.). The aggregation of all the data from the different houses as well as the calculation of individual or overall performance is ensured at this level. The data of each house is sent directly and in real time to the server PC, by the PLC installed there. This data is saved a second time in the memory of the server. Monitoring data are available via the knowledge platform for post-competition research.

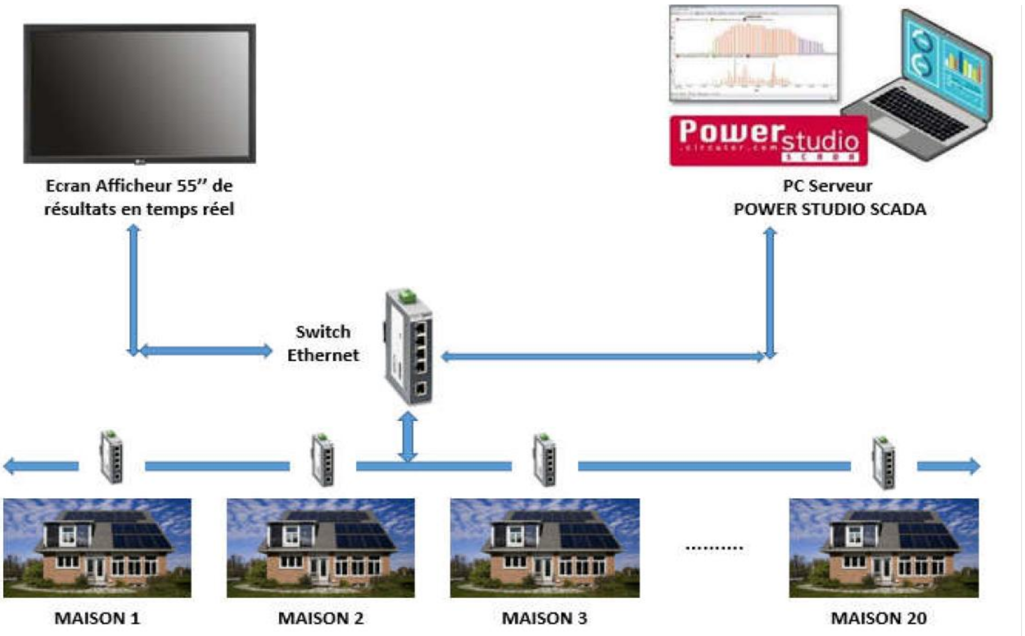

Figure 154: Communication and supervision Architecture of the monitoring System. Source: Samir Idrissi Kaitouni, IRESEN

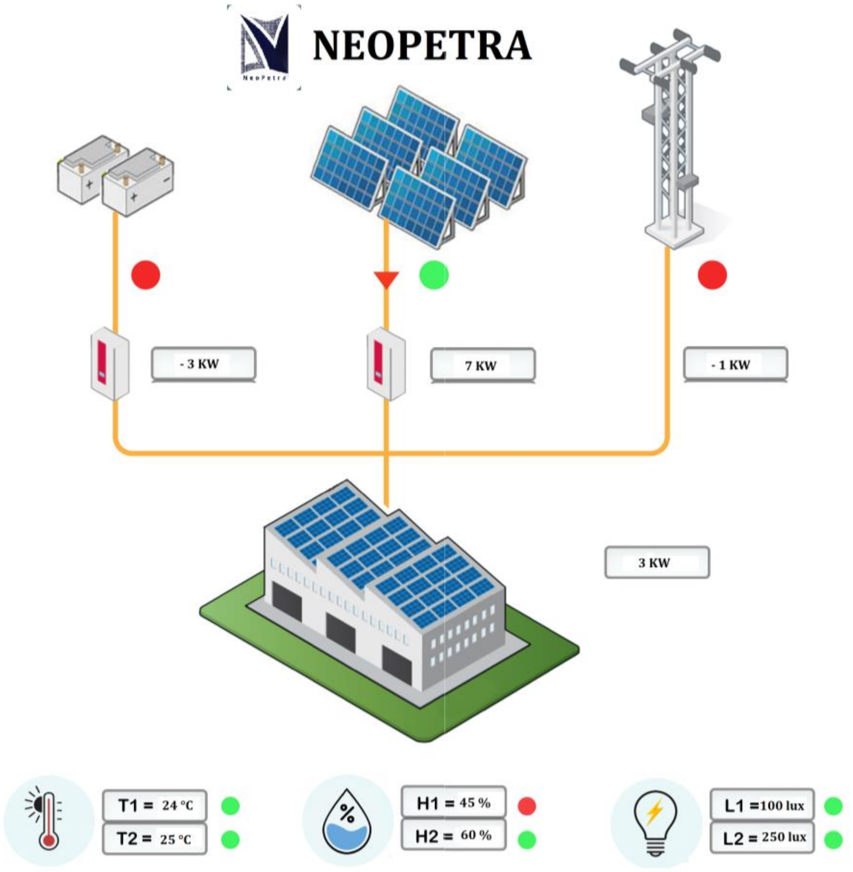

Figure 155: A scada interface developed for the real-time monitoring of the houses, Source: Samir Idrissi Kaitouni, IRESEN

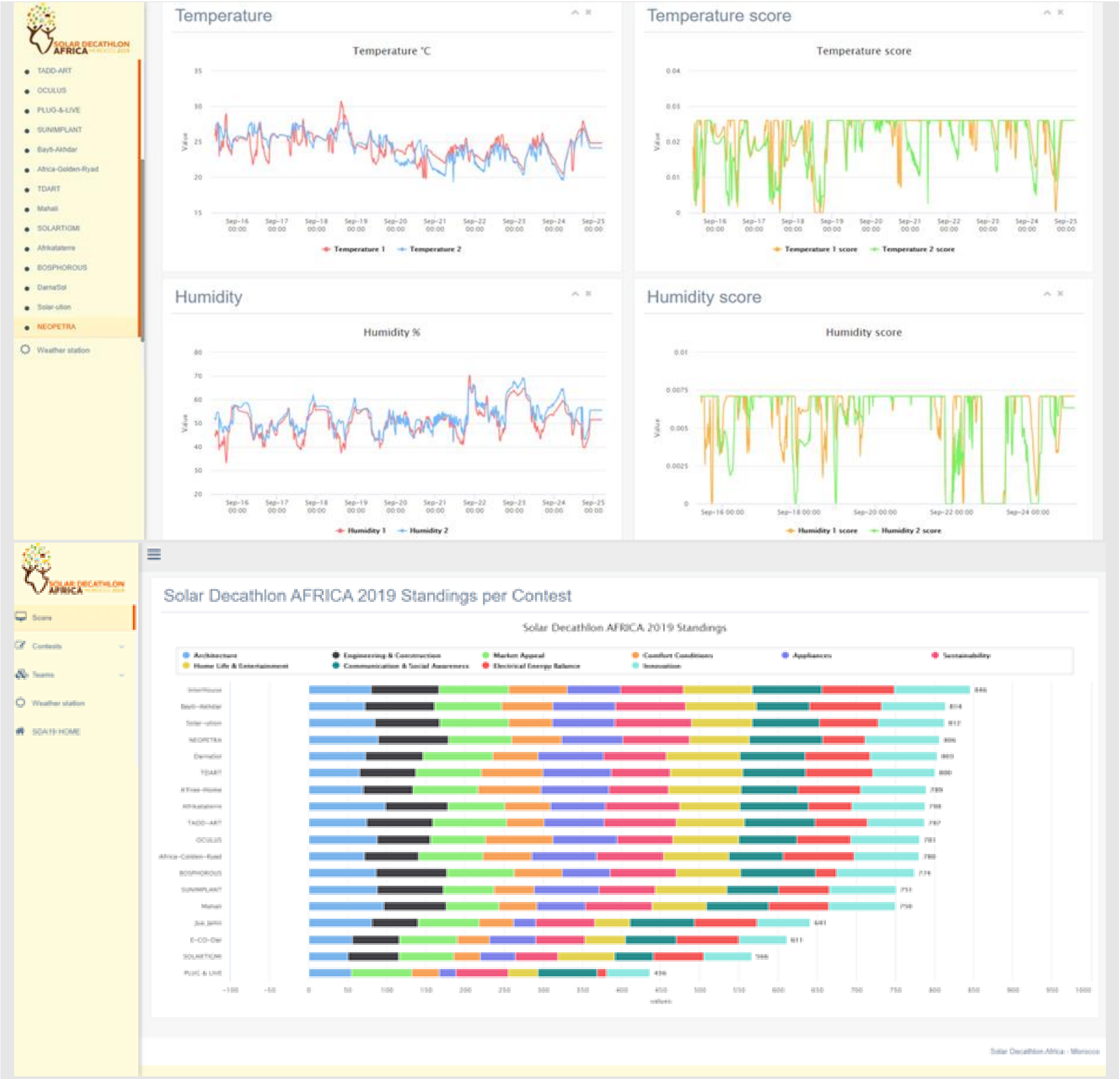

Figure 156: A web-based application developed for the centralization of all physical and scoring data, Source: Samir Idrissi Kaitouni, IRESEN

5. Topical Papers[25]

5.1 Objective

Within the IEA Technology Collaboration Program (IEA TCP) framework relevant research on building energy performance and renewable energy supply in the built environment was done and published recently. Namely in the Energy in Buildings and Communities TCP, Solar Heating and Cooling TCP and Heat Pump Technology TCP cover technical expertise related to living labs. The purpose of the report is to make these knowledge base available to those who are intending to participate in a living lab competition and those who are on the way to set up their own living lab. With a set of so-called topical papers experts from Annex 74 and other Annexes have summarized the state of the art and research on selected topics to allow a compact overview for future organizers and teams.

Chapter 5 contains the introduction and a compact presentation of the contents of the Annex 74 focus report "Topical Papers". This focus report comprises a total of 100 pages of information for the deepening of 11 individual topics. With the set of topical papers experts from Annex 74 and beyond have summarized the state of the art on selected topics to allow a compact overview for future organizers and teams.

5.2 Building Design and Architecture

In the topical papers give an insight into different aspect of the building design and on different technologies. This comprises design and building envelope related aspects like comfort, air tightness and architectural integration of solar systems. Conceptual and methodological approaches like modular buildings and passive houses are described as well. The following areas are addressed:

- thermal comfort
- air tightness
- modular building
- sustainability

5.3 Energy supply technologies

The related IEA TCPs are all supporting the exchange on research on renewable energy supply technologies, as they are key for a transition towards a climate friendly built environment. Namely heat pumps and solar systems with associated batteries are highlighted as they are common in single houses. Solutions on a district or city level gaining an increasing interest and importance are not here reflected, further information can easily be accessed via the web-platforms of the TCPs. In addition, an in depth insight into energy flexibility and human-machine interaction the field of operation and control is given:

- heat pumps
- solar thermal systems

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[25] Sebastian Herkel, Fraunhofer ISE

- photovoltaic
- hybrid solar systems
- batteries
- energy flexibility
- user friendliness

5.4 Papers Outline

Starting with a general overview, parameters and key performance indicators are described as well as simulation, monitoring procedures and analysing methods.
As example in Figure 157 the energy flows and boundary conditions for and performance evaluation of a heat pump system is given.

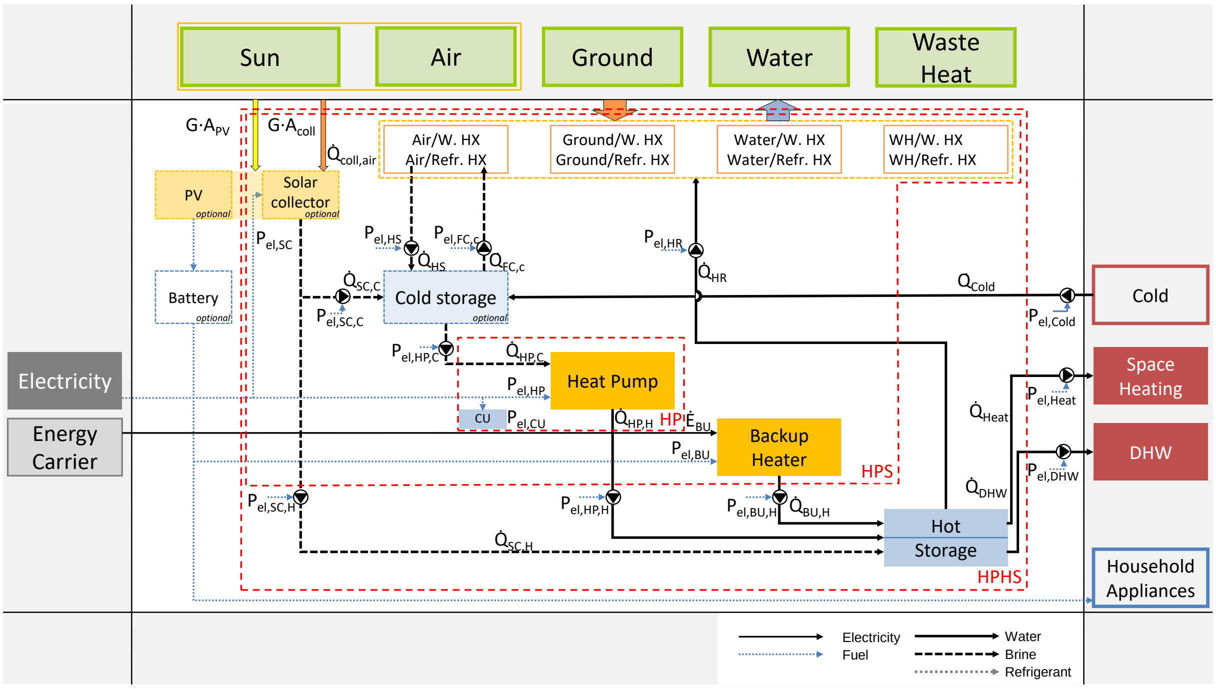

Figure 157: Example System boundary of a heat-pump based heating system. In the upper part the environmental heat sources and sinks at site are shown, on the left side energy delivered to the site and on the right the net energy delivered to the building. Using this systematic view both a performance evaluation based on simulation or measurements as well as a monitoring concept can be derived. Source: Fraunhofer ISE

Further readings are given to those, who like to deepen their knowledge giving an easier access to relevant publications. The set of papers presented within the report on topical papers are as well published online on the knowledge platform building-competition.org[26].

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[26] https://building-competition.org/material/show/TOPA

6. Stimulating Building Science in Competitions

One major aim of Annex 74 was to increase the link to building science in future competitions, namely the European editions of the Solar Decathlon. Within the review of past competitions in chapters 2 and 3, relevant publications were cited, which address building science topics by making use of the SD houses. The first competition which will profit from the work within the Annex will be the SDE21, taking place in June 2022 in Germany due to the worldwide pandemic[27]. The next might be the SDE23. Editions such as the SDE19, SDME18 or SDA18 were already profiled with their rules before significant output from the Annex was available. The experience with SDE21 will therefore form the test ground to judge the suitability of the SD concept for building science issues and their communication to the public.

The EBC as well as the SHC are official partners of SDE21. This is the first time the IEA has cooperated with the Solar Decathlon competition organizers and format.

6.1 Monitoring Structure[28]

As described in the previous chapters on the experiences from past competitions and documented with the monitoring data in the separate focus report 1, past monitoring was mainly designed for the purpose of a fair scoring in the competition. Post-competition research was not the intention. An initial information summary was presented with chapter 4.

Addressing building science after and crossing competitions creates the need for professionalizing and harmonizing the approaches (sampling frequency, averaging interval, etc.) and a more detailed documentation (sensor type, sensor positioning, etc.), preferable within the knowledge platform. Some performance indicators such as the self-consumption rate or the degree of self-sufficiency (refer to Figure 104) are mainly influenced by the time resolution of the data. The time stamp of the data (averaging method, daylight saving time, etc.) has to be described in detail. Sharing knowledge for a monitoring tender from past competitions has proven to be a major resource to better understand the needs and avoid mistakes. This was done within Annex 74 by adopting the SDME18 experiences for creating the call for tender for the monitoring service for SDE21. The Annex 74 knowledge platform is a suitable instrument to share such information in future.

As the competition final is an event, the schedule is very much influenced by event management aspects. Managing a large number of visitors creates the need for sufficient visiting times during the event to avoid long waiting lines and other logistic problems like transport etc. The typical solution in the past was the splitting of each day into monitoring/scoring periods and non-monitoring/scoring periods. This mainly addresses the comfort monitoring in the houses (temperature, humidity, air quality, and lighting level) whereas the energy monitoring continues all over the competition days. Teams have to manage the shift from an open house mode to a controlled indoor environment according to the needs of the comfort rules. This has two main consequences:

- Teams having systems with high capacity for heating/cooling are in favour compared to others using low-capacity systems.

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[27] www.sde21.eu

[28] author: Moritz Stark, University Wuppertal

- Monitoring data become not suitable for post-competition research as the time for controlled conditions is far too small. The measured indoor conditions are influenced by non-described parameters such as visitor numbers, user behaviour, etc.

Stimulating building science in competitions favours a schedule with a separation of “comfort days” and “public days”. SDE21 will, for the first time, address such an approach with two times three comfort days. Experiences will be gained regarding the post-competition research options.

The availability and quality of local weather data for the event period and some days ahead is a precondition to understand the building-related monitoring results beyond the scoring. Another issue is the data availability for the purpose of building and system simulation (refer to 6.5). The measurement conditions should be as far as possible close to the needs for metrological stations (sensor height above ground, free of shading, etc.). Typical data points needed are:

- Ambient temperature
- Global or direct normal radiation
- Diffuse radiation
- Rel. humidity
- Wind speed

As the radiation measurements – namely the splitting of direct and diffuse radiation - require the most expensive sensors, a compromise is the use of radiation data from a nearby, professionally operated weather station. It is also possible to record global radiation only and calculate the direct/diffuse split based on external weather station data. The split is important to receive sufficient accuracy when computing the radiation on inclined, diverse oriented surfaces (as for the solar systems). All other data should be monitored locally as they are highly sensitive to the location due to microclimatic effects. Based on such a data set, the measured climate conditions can be described with a weather data set in a suitable format for typical building and system simulation software (.epw, .try, etc).

6.2 Documentation Templates[29]

Design, planning and implementation of the contributions to a building competition such as the Solar Decathlon are a continuous process during the competition. A number of characteristic facts and indicators of the buildings are created, which identify in detail their properties and expectations.

In the context of the Annex, we have investigated the documentation of previous competitions. The ‘knowledge platform’ (https://building-competition.org) is an essential result. The work turned out to be complex, especially because quantitative information was hidden in extensive project manuals and at various chapters in them. In addition, as a result of the long-term project and different people working on the project, there were contradictions in the information given, e.g. inconstant numbers in the project manuals for the same indicators. The template now created is an outcome of common investigation and discussion within the Annex. It will be for the first time applied in SDE21. It is a target of the template called "Project Facts“ to systematically record and update the project information and indicators for the buildings and technical systems as a part of the team deliverables. The template might be linked to a systematic structure of all relevant data sheets of the products applied.

In SDE21, teams are working on the level of the design challenge (DC, level of overall building, not to be built) as well as the House Demonstration Unit (HDU, built on-site). Data are separately required for both levels within separate tables. The requested information for the house demonstration unit is more in-depth. The aim of the query is to receive the essential indicators and refer to more detailed information in the product sheet for each of the technical systems. These product sheets will be part of a platform with uniform document descriptions and file denomination. With each deliverable, the level of information on

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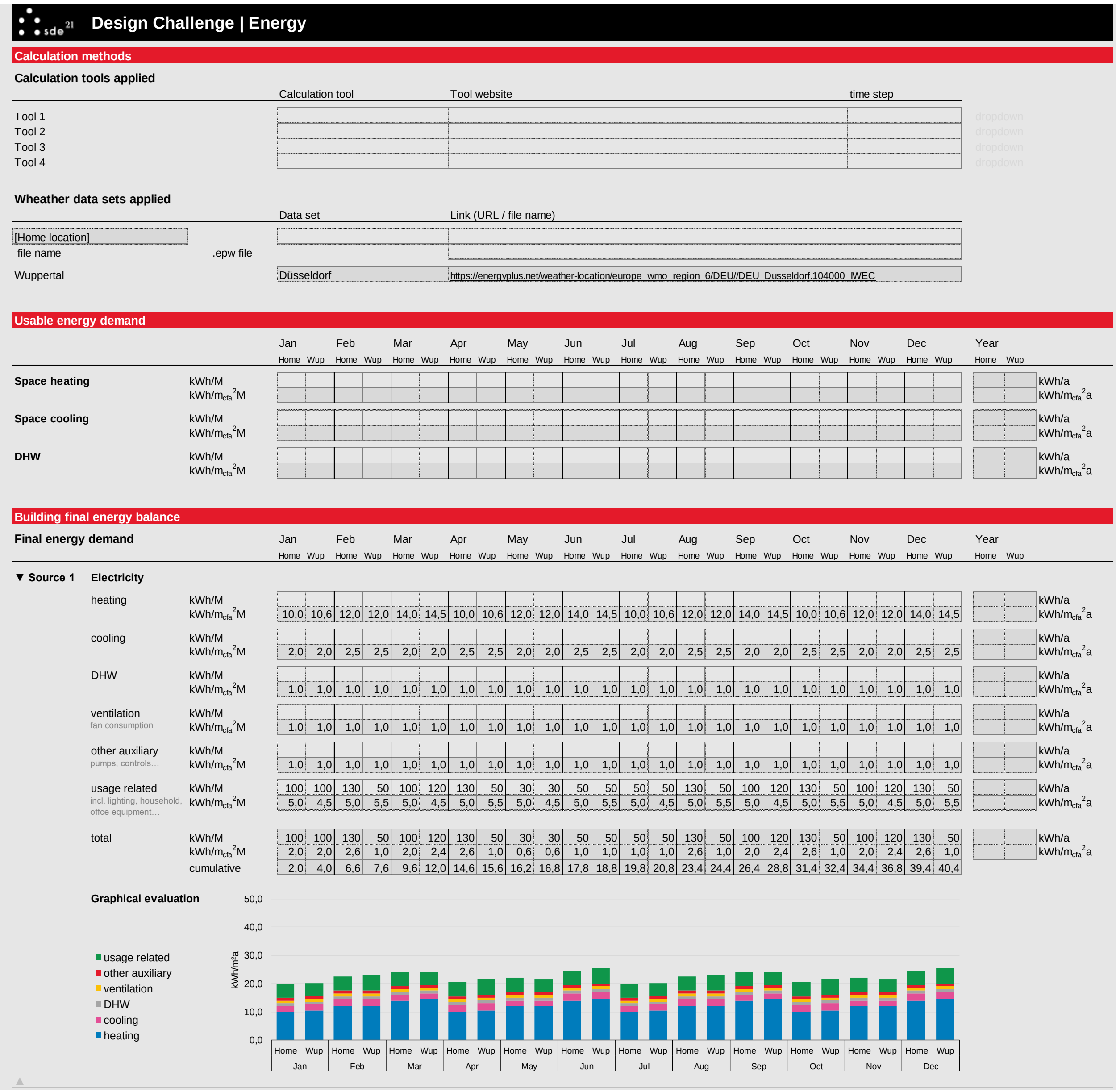
[29] author: Jan Martin Müller, University Wuppertal

project facts increases and corrections can be applied. The latest version is valid. With the last deliverable, the built status of each house demonstration unit is recorded.

The template is a set of Excel tables in one file. An example of such a table is illustrated with Figure 158. The full tables are part of the focus report 3 and the files are available online via the knowledge platform for later adaptation for new competitions.



sde 21 **Design Challenge | Energy**

Calculation methods

Calculation tools applied

	Calculation tool	Tool website	time step	
Tool 1				dropdown
Tool 2				dropdown
Tool 3				dropdown
Tool 4				dropdown

Wheather data sets applied

	Data set	Link (URL / file name)
[Home location]		
file name .epw file		
Wuppertal	Düsseldorf	https://energyplus.net/weather-location/europe_wmo_region_6/DEU//DEU_Dusseldorf.104000_IWEC

Usable energy demand

		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec		Year		
		Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	
Space heating	kWh/M																											kWh/a
	kWh/m_{cfa}^2M																											kWh/m_{cfa}^2a
Space cooling	kWh/M																											kWh/a
	kWh/m_{cfa}^2M																											kWh/m_{cfa}^2a
DHW	kWh/M																											kWh/a
	kWh/m_{cfa}^2M																											kWh/m_{cfa}^2a

Building final energy balance

Final energy demand

▼ Source 1 **Electricity**

		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec		Year		
		Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	Home	Wup	
heating	kWh/M																											kWh/a
	kWh/m_{cfa}^2M	10,0	10,6	12,0	12,0	14,0	14,5	10,0	10,6	12,0	12,0	14,0	14,5	10,0	10,6	12,0	12,0	14,0	14,5	10,0	10,6	12,0	12,0	14,0	14,5			kWh/m_{cfa}^2a
cooling	kWh/M																											kWh/a
	kWh/m_{cfa}^2M	2,0	2,0	2,5	2,5	2,0	2,0	2,5	2,5	2,0	2,0	2,5	2,5	2,0	2,0	2,5	2,5	2,0	2,0	2,5	2,5	2,0	2,0	2,5	2,5			kWh/m_{cfa}^2a
DHW	kWh/M																											kWh/a
	kWh/m_{cfa}^2M	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0			kWh/m_{cfa}^2a
ventilation	kWh/M																											kWh/a
fan consumption	kWh/m_{cfa}^2M	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0			kWh/m_{cfa}^2a
other auxiliary	kWh/M																											kWh/a
pumps, controls…	kWh/m_{cfa}^2M	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0			kWh/m_{cfa}^2a
usage related	kWh/M	100	100	130	50	100	120	130	50	30	30	50	50	50	50	130	50	100	120	130	50	100	120	130	50			kWh/a
incl. lighting, household, offce equipment…	kWh/m_{cfa}^2M	5,0	4,5	5,0	5,5	5,0	4,5	5,0	5,5	5,0	4,5	5,0	5,5	5,0	4,5	5,0	5,5	5,0	4,5	5,0	5,5	5,0	4,5	5,0	5,5			kWh/m_{cfa}^2a
total	kWh/M	100	100	130	50	100	120	130	50	30	30	50	50	50	50	130	50	100	120	130	50	100	120	130	50			kWh/a
	kWh/m_{cfa}^2M	2,0	2,0	2,6	1,0	2,0	2,4	2,6	1,0	0,6	0,6	1,0	1,0	1,0	1,0	2,6	1,0	2,0	2,4	2,6	1,0	2,0	2,4	2,6	1,0			kWh/m_{cfa}^2a
	cumulative	2,0	4,0	6,6	7,6	9,6	12,0	14,6	15,6	16,2	16,8	17,8	18,8	19,8	20,8	23,4	24,4	26,4	28,8	31,4	32,4	34,4	36,8	39,4	40,4			

Graphical evaluation

Figure 158: Example page of a fact sheet for a competition entry to SDE21, Source University Wuppertal

6.3 Performance Analysis of PV Systems[30]

As reported in chapter 3, the performance of technical systems such as ventilation units, solar thermal systems, heat pumps etc. was not under investigation with the monitoring approach of past competitions. In the history of the competition, the monitoring focuses on the whole house analysis for the scoring regarding energy and comfort instead of a system analysis. This was also triggered by consideration of the cost and

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[30] author: Moritz Stark, University Wuppertal

the time needed to create a full system analysis. Such analysis was left to the individual teams for research after the competition final phase.

Within Annex 74 a discussion took place if and how to include system analysis. As the PV integration is one of the main aspects in the whole SD history and a major factor for future buildings and building retrofits, a proposal was developed to include the so-called performance ratio analysis into the competition rules and the monitoring [County 2020-1]. As teams are developing and demonstrating the design and technical integration of PV systems in buildings it is important to sensitize for the critical factors of a well-done system and take it as part of the communication strategy.

The performance ratio gives the performance of the installation independent of the orientation and inclination of the panel. It typically ranges from 0.7 to 0.9. It includes all losses: temperature, inverter, DC cables, AC cables, panel mismatch, shadings, losses at weak radiation, and losses due to dust, snow, etc. According to IEC EN 612724 the performance ratio PR is defined as:

$$PR = \frac{Measured\ Production\ (kWh)(AC)}{Irradiation\ on\ panel\ \left(\frac{kWh}{m2}\right) \times A \times \eta_{STC}(DC)}$$

with A as the solar system area and η_{STC} as the solar panel efficiency at standard test conditions.

The additional investment needed for the monitoring are irradiation meters for the PV system per house (calibrated solar cell) to monitor the representative irradiation received by the panels. In the case of more than one PV system per house (roof plus façade installation) only the roof system will be analysed. The results are expressed as a cumulative performance ratio per installation for a defined period during the competition weeks in which all demonstration units are free of shadowing for direct radiation. Various weather and operation conditions are to be covered.

It is the aim of the investigation to underline the need for convincing system design and building integration and focusing not only on large systems with high output compared to the building energy needs. This is an important message with regard to the education of students and may increase the interest of the solar industry to demonstrate high performance systems.

Compared to the analysis of other technical components (solar thermal, heat pumps, ventilation, etc.), this investigation doesn’t need much investment or additional monitoring time. Experience will be made regarding the scientific relevance of the investigation (journal papers, etc.).

6.4 Building Grid Interaction[31]

The growing share of renewable energies in the distribution network is increasingly leading to new challenges. Unsteady feed-in behaviour over the course of the day, the expansion of electro-mobility and the increased use of heat pumps can lead to a drop in grid voltage and to thermal overload of electrical equipment such as cables or transformers. A paradigm shift in consumption behaviour will have to be implemented in future in order to minimize the expensive grid expansion required to compensate for this. Where previously generation has followed consumption, in the future consumption must follow generation. In order to give the teams and visitors to the Solar Decathlon an insight into this problem and to present the building as part of the solution, grid related sub-contests have been created over the years (refer to chapter 3.6). Research in the framework of SDE 2012 has addressed such topics using the solar village as a case study [li 2019]. EBC Annex 67 “Energy Flexible Buildings” has provided a knowledge platform related to methods and key indicators to evaluate the interaction of buildings and the power grid [iea ebc annex 67]. Table 18 shows these grid-related sub-contests for the 2014, 2018, 2019, and 2021 Solar Decathlon editions. In the years 2010 and 2012, the main focus was on the energy balance and the degree of self-

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[31] author: Moritz Stark, University Wuppertal

sufficiency. It can be seen that over the years, the number, the content, and the weighting have remained approximately the same in absolute terms. The sub-contest can be divided into two categories: on the one hand, the avoidance of peak loads and on the other hand, the time shift of electrical consumption through the introduction of a (dynamic) electricity tariff.

Table 18: Grid related sub-contests, Source: University Wuppertal, Moritz Stark

Competition	Sub-Contest	Points
SDE14	House adjustment to network load state	20
	Power peaks	15
SDME18	Demand response	20
SDE19	House adjustment to network load state	20
	Power peaks	15
SDE21	Grid interaction (privileged feed-In, demand-side management)	30

In Versailles at SDE 2014 and in Szentendre at SDE 2019, the grid related sub-contests addressed the avoidance of peak loads and flexible electricity tariffs. The latter were rigid and consisted of a high and low tariff phase. Thus, teams were rewarded who avoided electricity consumption in the evening hours or fed in additional energy into the low-voltage grid. At the SDME in Dubai on the other hand, the sub-contest demand response was only used to encourage a shift from the lunchtime and afternoon hours, and there was no reward for feeding power into the grid at specific times.

Based on the experiences and the discussion with EBC Annex 74, a more complex competition design was developed for SDE 2021. To gain points, it will be necessary to use building management systems and the previously rigid tasks have been replaced by dynamic tasks. As described above, in previous competitions a fixed tariff structure applied throughout the entire competition period, whereas in the SDE21, the teams are only informed one day ahead of time, how the electricity costs will change during the course of the day. In addition, in the task privileged feed-in, the teams have to prove that they can distribute their consumption the following day flexibly enough so that a noticeable reduction can be seen in the morning hours.

Figure 159 shows that points were transferred from the initially strongly weighted energy balance to the grid related sub-contests, which are now roughly as strongly weighted as the area-related consumption. In the history of the competition, these sub-contests have not gained any further relevance relative to the total number of points despite increasing requirements. SDE21, however, offers technically experienced teams a chance to stand out from the rest for the first time due to the increased complexity of the tasks.

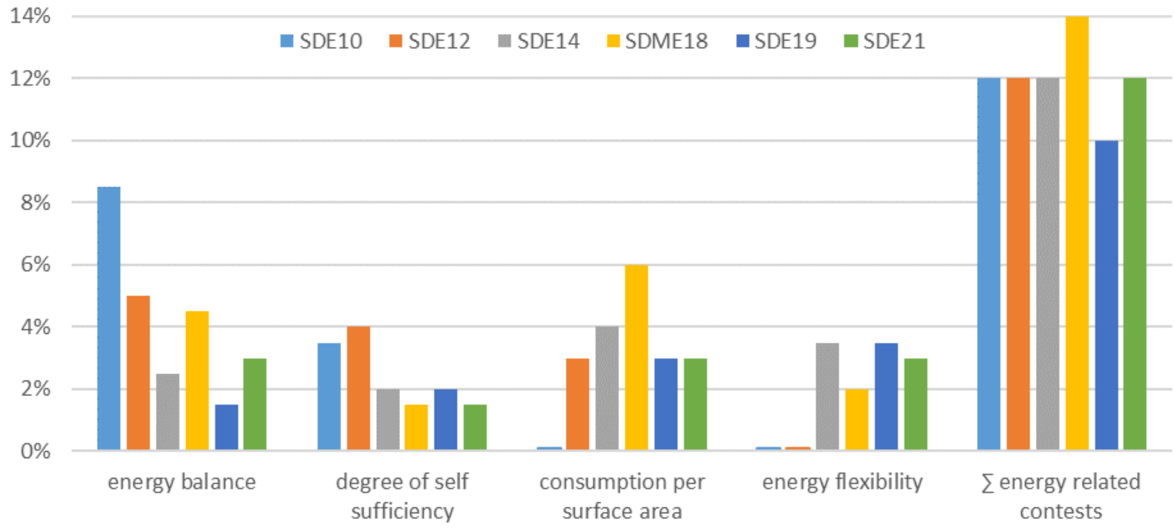

Figure 159: Achievable maximum score of the energy-related sub-contests relative to the total score of the respective competition (1,000 points), Source: University Wuppertal, Moritz Stark

It is advantageous that no additional measuring equipment is required for the new grid related sub-contests. Energy meters, which are necessary for the evaluation of the balance, the self-consumption and the area-related consumption, meet the requirements completely. If high-quality measuring devices are used in the houses, which can record grid condition data (voltage, current, phase angle ...), additional scientific investigations can be carried out. This was proven by the use of the monitoring data from SDME 2018 (refer to sub report 1). SDE21 will also collect additional grid-condition data for the entire campus grid at a central location. Future competitions might address energy flexibility as an important issue even more.

6.5 Thermal Building Performance

In the interest of comfort and overall quality insurance, blower-door tests are a suitable method to control the airtightness value. A description of the method is available with a dedicated topical paper referring to the relevant EBC activities [bossche 2020]. Such tests have been mentioned in the SDE14 and SDE19 rules but have not come to practical application in these competitions. They are planned for SDE21 as part of the scientific approach and to make the student teams aware of quality assurance for buildings. Of course, the student-built buildings and the limited assembly time have to be considered when discussing the results. On the other hand, it’s a main didactic principle to make the student aware on the role of convincing detailing and the implementation phase.

There are a number of parameters to describe the thermal performance of total buildings. Whereas envelope components are characterized and tested for properties such as U-values or solar gain coefficients (glazing only), whole buildings are characterized by overall heat loss and solar gain coefficients together with identification of the thermal mass. The overall characterization is mainly of interest for testing and checking of the performance gap between simulation and real operation. It integrates all main effects such as insulation and transparency as well as secondary effects such as thermal bridges, air tightness, shading, etc. into fewer key performance indicators.

The Annex 71 “Building Energy Performance Assessment Based on in-situ Measurements” within the EBC program focuses on dynamic in-situ testing of the properties of buildings and their components and is the follow up of the former Annex 58[32]. The work is very much related to the “DYNASTEE” network.

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[32] https://bwk.kuleuven.be/bwf/projects/annex71/

DYNASTEE stands for: "DYNamic Analysis, Simulation and Testing applied to the Energy and Environmental performance of buildings". DYNASTEE is an informal grouping of organizations actively involved in the application of tools and methodologies relative to this field[33].
Based on the work published from these networks, so-called co-heating tests have been discussed in EBC Annex 74 for application in the SD competition and investigations have been performed especially for the implementation within SDE21. A classical co-heating test is based on heating a building in the cold season by regulated electric heaters up to constant indoor temperature level, well above ambient conditions over a period of a few weeks. The static analysis is then based on the relation of the recorded heating power to the temperature difference on a daily basis to determine an overall heat loss coefficient [phi 2016]. Such a procedure is too time consuming for a tight competition schedule. Further to that, the competitions take place in the warm and sunny season with not enough difference between indoor and outdoor temperatures and partly high solar gains interfering with the heat flow from inside to outside.

6.5.1 Pre-Investigations[34]

Pre-investigations have been performed by experiments as well as simulation studies.
The Annex members from University of Applied Science Fribourg, Switzerland, have investigated the thermal behaviour of two test rooms on the campus resulting from co-heating experiments [boes 2019-1] [boes 2019-2]. Figure 160 illustrates the arrangement of the building with its two identical office rooms. For the purpose of the co-heating test, the two rooms have been heated in four different cycles by 2 kW electric heaters. Ventilation have been switched off and no internal heat gains occur. Data have been recorded with a sampling interval of two minutes. Figure 161 illustrate the monitoring results for the cycles one and two. Despite out-of-equilibrium initial conditions, the measurement campaign demonstrated a repeatability in the thermal signatures of the heating-cooling cycles in two separate test rooms. From these initial measurements, it would appear that the thermal signature is influenced not only by its inertia (i.e. its ability to store energy) but also by the amount of energy stored in its walls when starting the experiment. For this reason, identical start conditions for the capacity charging are very important for replicable experiments. The numerical modelling of the experiment by a simplified resistance-capacity model underlines the important role of the thermal charging status at the beginning.

Figure 160: Test building with two identical rooms at the university campus in Fribourg, Switzerland (left and right). Source: University of Applied Science and Arts Western Switzerland [boes 2019-1]

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[33] https://dynastee.info/data-analysis/overview/

[34] author: Karsten Voss, University Wuppertal

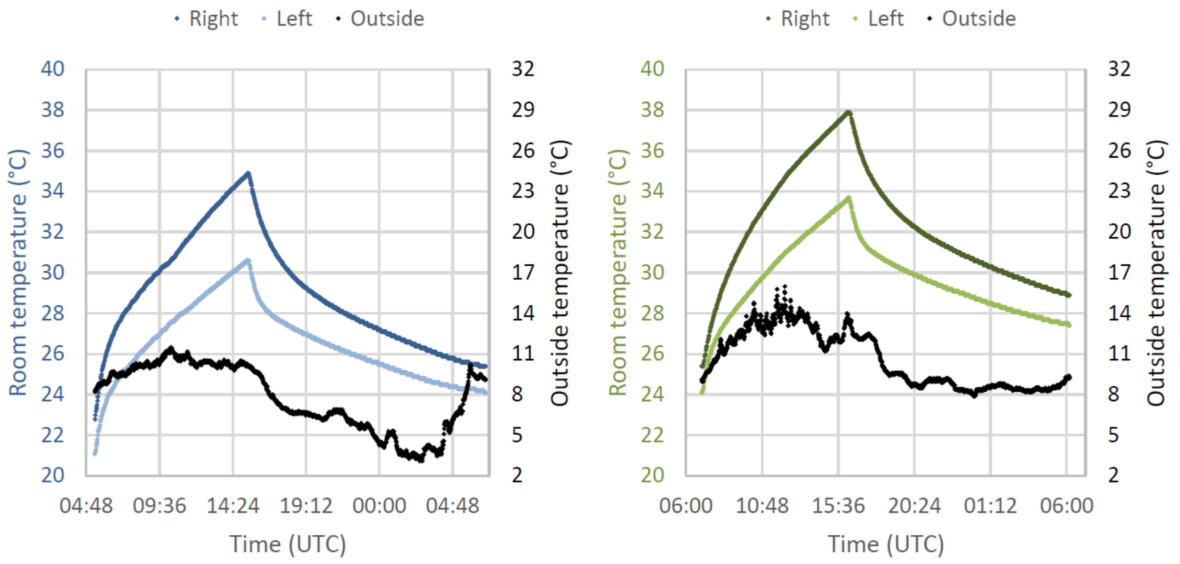

Figure 161: Documentation of the heating experiments with the two office rooms in Fribourg, Switzerland for two different periods (left and right). Source: University of Applied Science and Arts Western Switzerland [boes 2019-1]

Researchers from the University of Arts in Berlin have implemented a co-heating test in their home from SDE 2014, re-established on the university campus in Berlin as a living lab[35]. Figure 162 illustrates the temperature reaction of the SDE 2014 house “Rooftop” after heating to 40°C with a 4.4 kW electric heater in July 2019. The indoor air temperature was stabilized at about 40°C for about 36 hours. The free-floating temperature reaches “normal conditions” after roughly 50 hours under typical early summer outdoor conditions. Shading systems were closed and the mechanical ventilation switched of during the experiment.

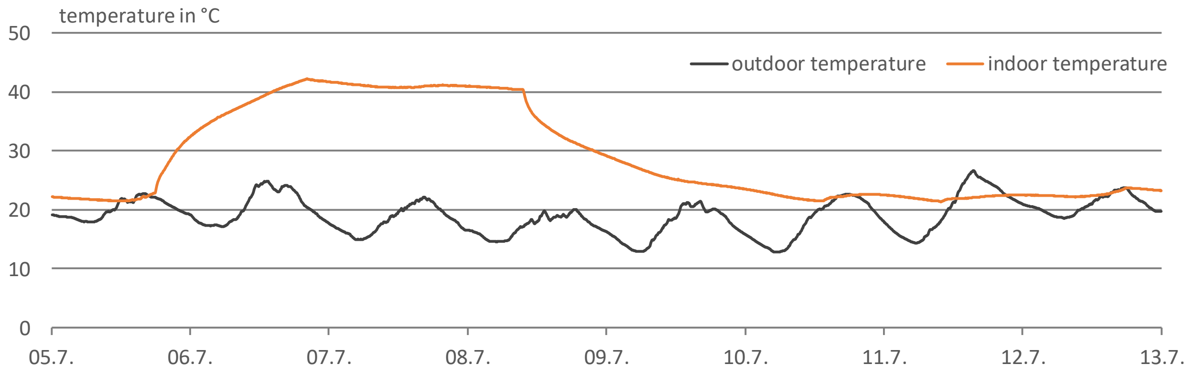

Figure 162: Documentation of the heating experiment with the Rooftop house in Berlin. The heater was switched off at 9 am on July 8th. Source: Chr. Nytsch-Geusen, UDK Berlin

6.5.2 Dynamic Co-Heating Test Design[36]

Based on the investigations within Annex 74 the SDE21 organizers will implement a "dynamic co-heating test" to allow an in-situ thermal characterization of all the demonstration houses. This test will be performed during six days between the final assembly and start of the competition’s final event. The first three days are intended for the temperature conditioning of the houses and the measurements of the air tightness, the following three days allow heating sequences with defined capacity and/or temperature set points. The

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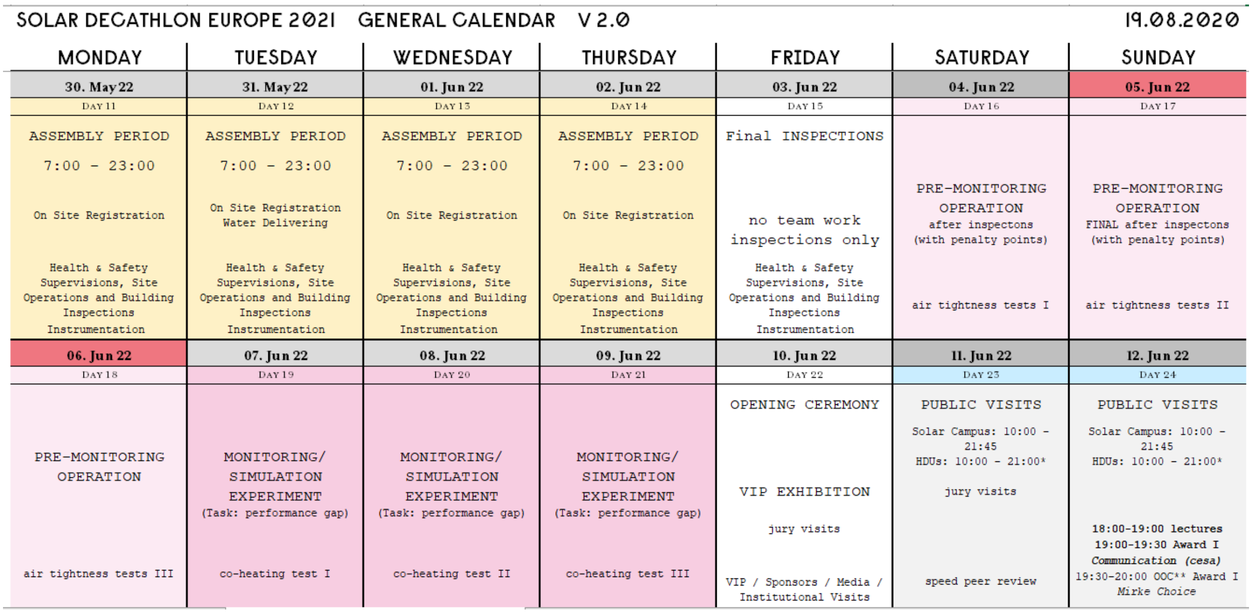
[35] http://www.solar-rooftop.de/

[36] author: Karl Walther, University Wuppertal

heating energy will be delivered by extra equipment temporarily installed in each house by the organizers and not counted for the energy competition. The heaters will be assisted by fans to ensure an equalized temperature within each house (single zone approach). As a result of the pre-investigations, all houses will be heated to identical indoor temperature slightly above the ambient temperature to start with harmonized thermal mass activation status.



SOLAR DECATHLON EUROPE 2021 GENERAL CALENDAR V 2.0 19.08.2020

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
30. May 22	**31. May 22**	**01. Jun 22**	**02. Jun 22**	**03. Jun 22**	**04. Jun 22**	**05. Jun 22**
DAY 11	DAY 12	DAY 13	DAY 14	DAY 15	DAY 16	DAY 17
ASSEMBLY PERIOD 7:00 - 23:00 On Site Registration Health & Safety Supervisions, Site Operations and Building Inspections Instrumentation	ASSEMBLY PERIOD 7:00 - 23:00 On Site Registration Water Delivering Health & Safety Supervisions, Site Operations and Building Inspections Instrumentation	ASSEMBLY PERIOD 7:00 - 23:00 On Site Registration Health & Safety Supervisions, Site Operations and Building Inspections Instrumentation	ASSEMBLY PERIOD 7:00 - 23:00 On Site Registration Health & Safety Supervisions, Site Operations and Building Inspections Instrumentation	Final INSPECTIONS no team work inspections only Health & Safety Supervisions, Site Operations and Building Inspections Instrumentation	PRE-MONITORING OPERATION after inspectons (with penalty points) air tightness tests I	PRE-MONITORING OPERATION FINAL after inspectons (with penalty points) air tightness tests II
06. Jun 22	**07. Jun 22**	**08. Jun 22**	**09. Jun 22**	**10. Jun 22**	**11. Jun 22**	**12. Jun 22**
DAY 18	DAY 19	DAY 20	DAY 21	DAY 22	DAY 23	DAY 24
PRE-MONITORING OPERATION air tightness tests III	MONITORING/ SIMULATION EXPERIMENT (Task: performance gap) co-heating test I	MONITORING/ SIMULATION EXPERIMENT (Task: performance gap) co-heating test II	MONITORING/ SIMULATION EXPERIMENT (Task: performance gap) co-heating test III	OPENING CEREMONY VIP EXHIBITION jury visits VIP / Sponsors / Media / Institutional Visits	PUBLIC VISITS Solar Campus: 10:00 - 21:45 HDUs: 10:00 - 21:00* jury visits speed peer review	PUBLIC VISITS Solar Campus: 10:00 - 21:45 HDUs: 10:00 - 21:00* **18:00-19:00 lectures** **19:00-19:30 Award I *Communication (cesa)*** 19:30-20:00 OOC** Award I *Mirke Choice*

Figure 163: The SDE21 competition schedule including the air-infiltration and co-heating test before the competition final, days 16 to 21. Source: University Wuppertal

The indoor temperature of all houses and the external climatic conditions will be monitored continuously with a high time resolution. A full climate data set of this period is handed to each team together with the request for simulating the thermal performance of the house in the monitored period. Simulations have to be performed for each of the houses with the identical tool (SimRoom), delivered by the organizers (refer to chapter 6.5.3). As this is the first time with such testing in the competition framework, the points for the teams will be awarded just for the task completion (i.e. delivery of the model file), not for the quality of simulation and not to compare and rank the houses. The organizers will compare modelling and simulation to detect the differences, reasons for them, and to give this knowledge back to the teams.

Within a detailed simulation investigation using IDA ICE 4.8, the design of the experimental procedure was investigated in detail and documented [walther 2020]. The first aim was to guarantee equal start conditions under different climatic conditions and different architectural designs and secondly, that the thermal performance is tested with regard to different influences such as solar gains, thermal losses, and co-heating. Due to the limited time available and the moderate outdoor temperatures, a full parameter identification is not realistic to achieve (heat loss coefficient, heat gain coefficient, thermal capacity).

The total duration is divided into 3 days of conditioning and 3 days of observation containing free floating, heating and solar impulses. Before the experiment, final works will take place during the buildings' completion. High ventilation rates without any heating or cooling are assumed in this phase. The aim of the conditioning phase is to heat up the internal masses of each house to equal temperatures and therefore guarantee equal steady-state starting conditions. A target temperature of 25 °C is chosen to avoid long conditioning times at unfavourable outdoor temperatures. This temperature has to be ensured for all building designs and especially different climate conditions. To prevent from temperatures above the heating set point during the conditioning phase, solar gains have to be minimized by closing all shading devices.

During the 3 days of observation different thermal behaviour is possible. To investigate a wide range of thermal performance, preferably all of them should occur.

- Heating up by solar gains during daytime depends on the occurrence of solar gains (climate). To ensure a high and measurable impact of solar gains, all shading devices have to be deactivated during the observation phase.
- Cooling down due to transmission and infiltration losses. This may be observed on cold days during daytime, which may still occur at the beginning of June, but definitively during night-time.
- Heating up due to activated heating systems. This should start from a moderate level (e.g. after a cooling down phase) and not after a heating up to solar gains with high indoor temperatures. Therefore, two heating up impulses are scheduled from 00:00 to 06:00.

No cooling or ventilation is applied at any time. The procedure is summarized in Table 19:

Table 19: Schedule of the experiment

	Phase	From	To	shading	heating	ventilation
1	conditioning phase	03.06.2022 18:00	06.06.2022 22:00	Down	Target 25 °C	Off
2	Free floating 1	06.06.2020 22:00	08.06.2022 00:00	Up	Off	Off
3	Heating impulse 1	08.06.2022 00:00	08.06.2022 06:00	Up	3 kW	Off
4	Free floating 2	08.06.2020 06:00	09.06.2020 00:00	Up	Off	Off
5	Heating impulse 2	09.06.2022 00:00	09.06.2022 06:00	Up	3 kW	Off
6	Free floating 3	09.06.2022 06:00	09.06.2022 24:00	up	Off	Off

The basic geometry and thermal properties are based on Wuppertal’s Solar Decathlon 2010 house (refer to Figure 89). The house is geometrically stretched to adopt to the larger floor areas allowed with the SDE21 rules. The simulation is conducted as a 1-zone-model. The heating power is limited to 3 kW to allow using a single-phase connection in the houses. The power limit allows to operate the electric heaters with single phase connection within the houses’ grid.
The results are investigated for different climate data sets and a selection of different starting days within the weather files as the weather at the completion time can vary largely. Thus, the experiment has to be defined robust enough to work within the real conditions. The graphs show the mean air temperature of the 1-zone model. Full results are provided with a detail report [walther 2020]. Different climatic conditions can lead to different temperature profiles during the observation phase. A colder climate with little solar radiation can lead to a temperature profile close to the initial steady state condition. In such a case, the stimulation by activated heating systems becomes more relevant. In contrast, warmer climate and/or high solar radiation can result in temperature level far above the initial steady state.

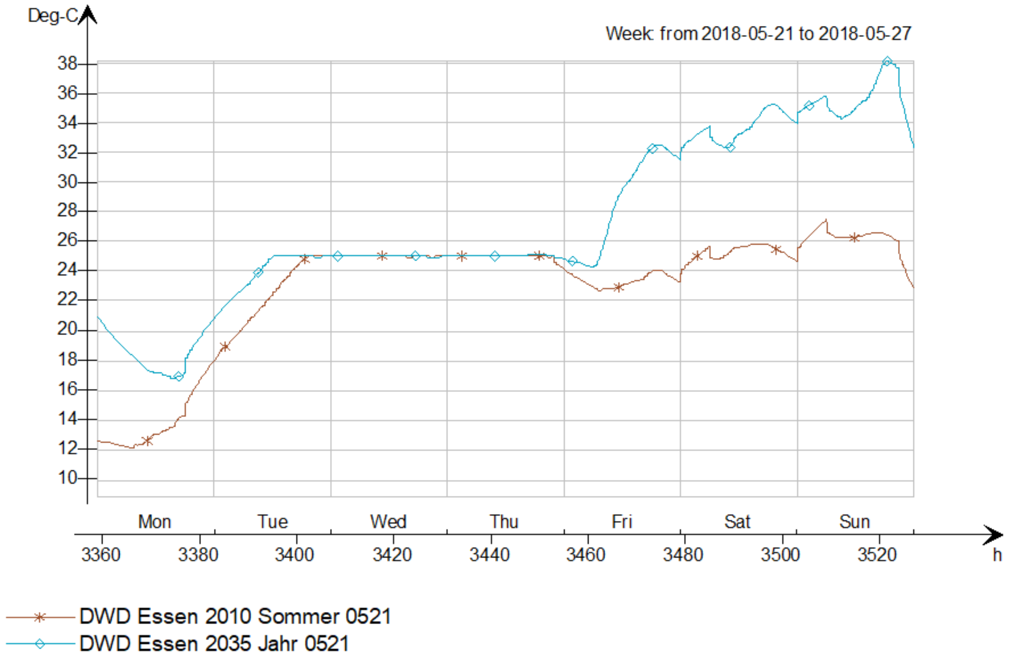


Figure 164: Indoor air temperature development during the experiment for two optional climatic data sets of the location. The data set 2035 represents a warmer climate due to global warming effects. Source: [walther 2020]

Solar irradiance in particular also affects the conditioning phase. High irradiation can lead to overheating (“overcharging”) of the zone. To minimize solar gains during the conditioning phase, activated shading systems have to be ensured by all means. Since the reduction factor $F_c = 0.05$ of the initial calculation is extreme, Figure 165 shows the influence of a more permeable shading device with $F_c = 0.2$ which would result in a total energy transmission rate $g_{total} = 0.5 * 0.2 = 0.1$. In such unfavourable designs together with sunny days during the conditioning phase, additional measures such as additional masking of windows may be taken into account and/or the conditioning set point may be increased to 30°C.

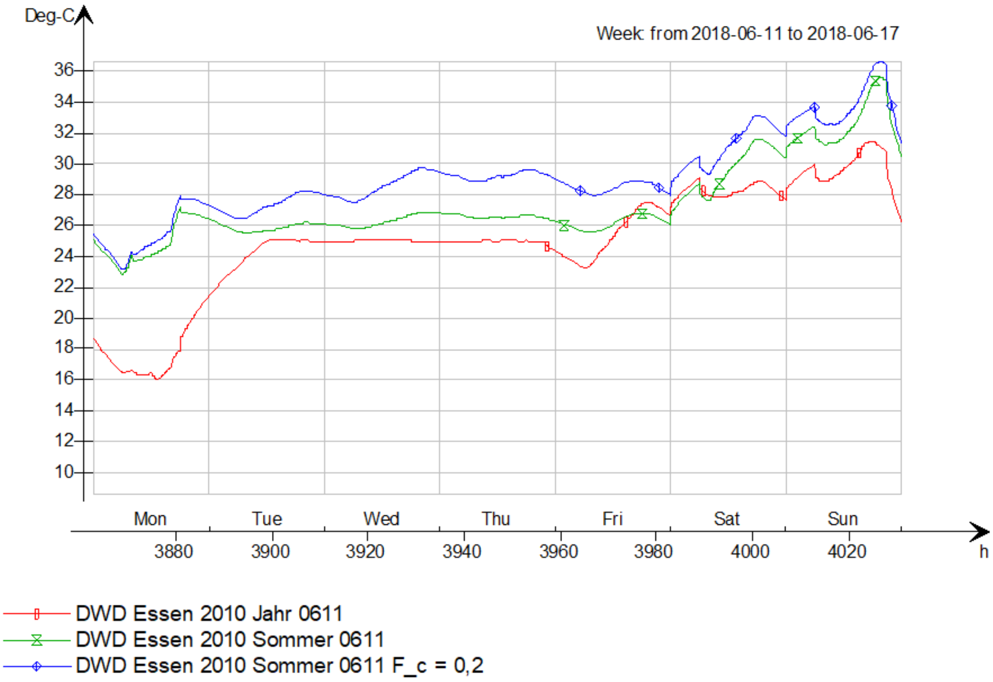


Figure 165: Temperature development during the experiment with different efficiency of the shading devices. Source: [walther 2020]

Figure 166 shows the influence of different internal masses and demonstrates that the internal masses reach the target temperature of 25 °C in any case at the end of the conditioning phase. The calculation “int. mass. x4” represents a very unfavourable case with 400 m² of furniture (3 cm wood) and 400 m² of internal walls with 3 layers of gypsum plasterboard on both sides.

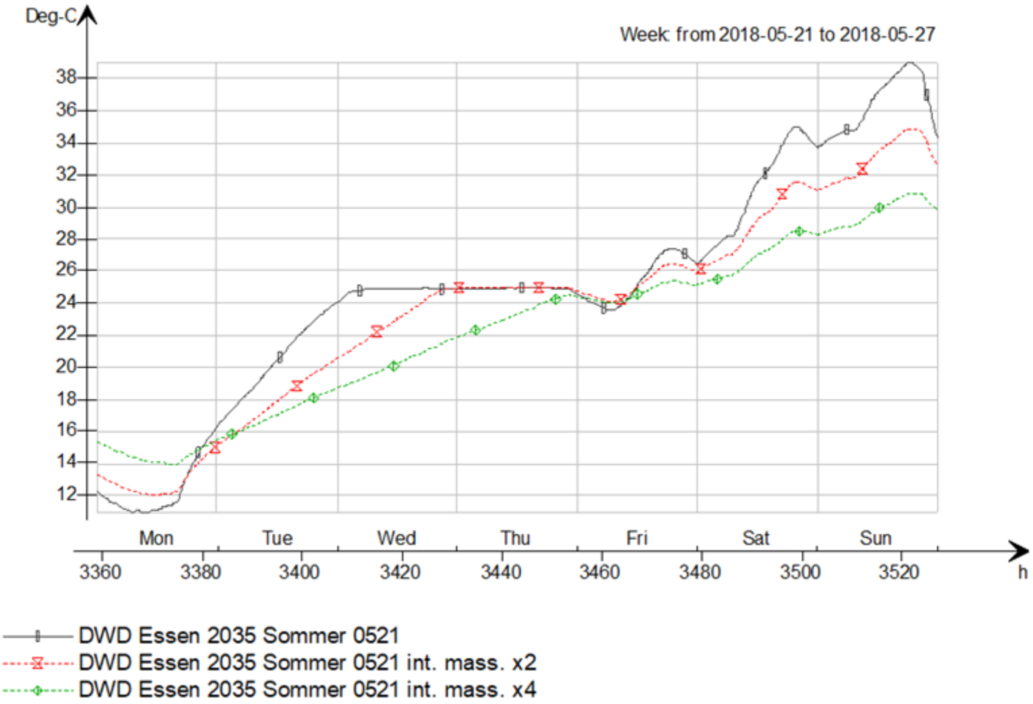


Figure 166: Temperature development during the experiment with increased mass within the house. Source: [walther 2020]

Based on the present simulation study, a preliminary experiment design for a co-heating test has been developed. The influence of different climatic conditions has been illustrated as well as different internal masses and glazing parameters. Particular attention has to be paid to the reduction of solar gains during the conditioning phase by fully closing all shading devices to prevent overheating.

6.5.3 Performance Simulation Tool[37]

The thermal performance testing leads to a qualified monitored data set regarding the transient indoor climate responding to outdoor climate and stimulation by co-heating. Using the monitored climate data and the schedule and power settings from the co-heating test allows to set up a simulation model for comparison. When using a validated simulation tool, the differences in the thermal behaviour may result from wrong assumptions when setting up the model or shortcomings in the construction and assembly of the demonstration unit (air tightness, thermal bridges, etc.).

Within SDE21, all teams have to deliver a dynamic simulation model based on the same single zone simulation tool "SimRoom". SimRoom offers the possibility of computing room temperature, air quality and humidity captured in hourly increments for a zone with relatively little input effort. The simulation can either refer to an individual room, a zone, or a building as a one-zone model. An energy balance at a building level incorporates heat generation, cooling, PV installations and battery storage, as well as the electricity demand of the building and the users. The simulation takes into account the insulation, the building material masses, the glazing, the sun protection and the ventilation, and carries out the calculation based on climate data captured on an hourly basis. Internal heat sources and user behaviour regarding sun protection and the natural and mechanical ventilation are all included. Settings are suggested in numerous places and guidance is given for the user to select. The basis of the program is the spreadsheet tool Microsoft Excel. The tool is made freely available for education by the developer[38]. A special edition has been set up for SDE21. The download link, a manual and a tutorial are available via the education section of the knowledge platform[39].

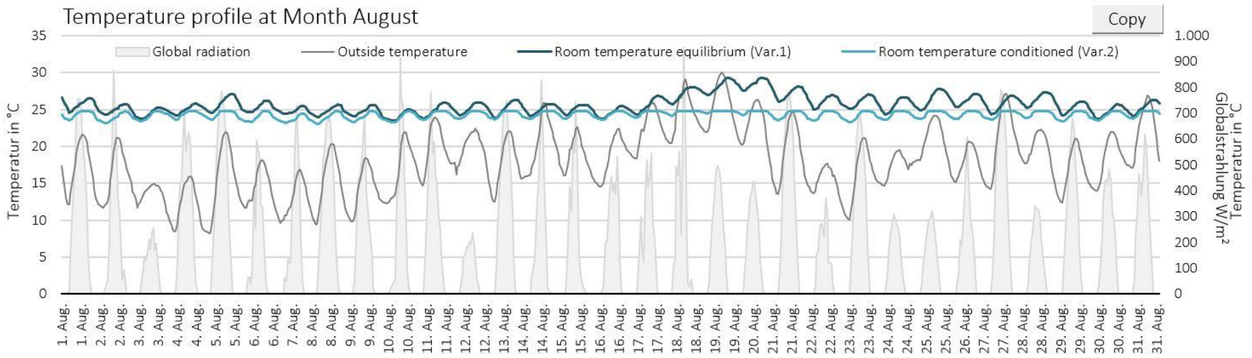


Figure 167: Typical output of the SimRoom tool with the comparison of the indoor temperature development of the building in the conditioned (cooling) and non-conditioned case. Source: Markus Lichtmeß, https://www.ingefo.de/Werkzeuge/SimRoom/

6.6 User Friendliness Evaluation Framework[40]

IT systems play an increasingly important role in buildings, whether for monitoring, control or interfacing with users. With current digitalization trends, sensors and automation systems are more and more often connected to internet, allowing the development of cloud- and data science-based services. With ever-

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[37] author: Karsten Voss, University Wuppertal

[38] Dr. Markus Lichtmeß, https://www.ingefo.de/Werkzeuge/SimRoom/

[39] https://building-competition.org/software/show/SIMROOM

[40] author: Jean-Philippe Bacher, Haute école d'ingénierie et d'architecture de Fribourg

increasing requirements in terms of energy efficiency and user comfort, efficient system integration and well-performing human-building interfaces are becoming extremely important. User-behaviour is nowadays recognized as one of the factors responsible for the energy efficiency performance gap often observed in buildings.

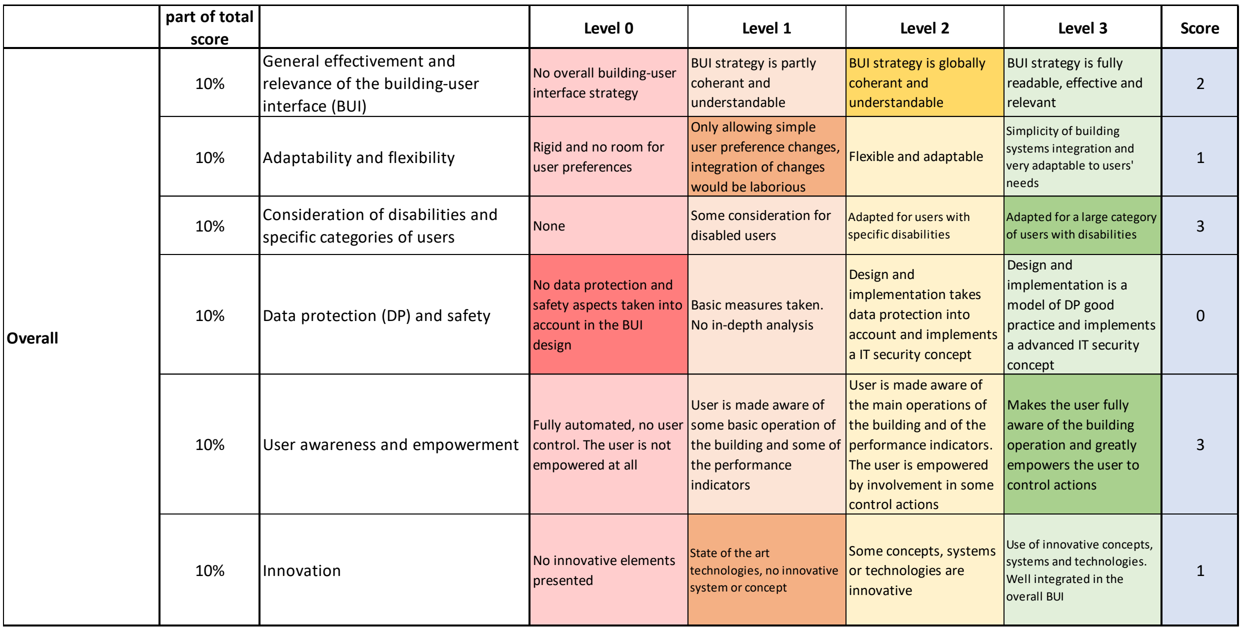
HVAC systems control, lighting control, occupancy aware control systems, security services, remote care or access right management, many building services may be provided or optimized with the support of IT- and automation- technologies. While scientific knowledge and technologies are evolving rapidly in this specific field, concrete implementation and transfer to practice often show many shortcomings and limitations.

Many aspects have to be taken into consideration when designing smart-homes and smart-buildings. To name just a few: general relevance and coherence with the building physics and building operation, user acceptance, inter-operability of sub-systems, performance monitoring, data protection, IT-security, and obsolescence. Building competitions and living labs provide a very valuable field of experimentation, with full-scale real buildings and possible interactions with users and visitors.

A framework is proposed to assess user experience when operating the building. The framework covers topics related to

- general effectiveness and relevance,
- reliability and usability
- self-descriptiveness
- controllability
- adaptability and flexibility
- consideration of disabilities and specific categories of users
- data protection and safety
- user awareness and empowerment
- innovation.

The proposed framework was developed and will be used in the context of the SDE21 competition (Figure 170).



	part of total score		Level 0	Level 1	Level 2	Level 3	Score
Overall	10%	General effectivement and relevance of the building-user interface (BUI)	No overall building-user interface strategy	BUI strategy is partly coherant and understandable	BUI strategy is globally coherant and understandable	BUI strategy is fully readable, effective and relevant	2
	10%	Adaptability and flexibility	Rigid and no room for user preferences	Only allowing simple user preference changes, integration of changes would be laborious	Flexible and adaptable	Simplicity of building systems integration and very adaptable to users' needs	1
	10%	Consideration of disabilities and specific categories of users	None	Some consideration for disabled users	Adapted for users with specific disabilities	Adapted for a large category of users with disabilities	3
	10%	Data protection (DP) and safety	No data protection and safety aspects taken into account in the BUI design	Basic measures taken. No in-depth analysis	Design and implementation takes data protection into account and implements a IT security concept	Design and implementation is a model of DP good practice and implements a advanced IT security concept	0
	10%	User awareness and empowerment	Fully automated, no user control. The user is not empowered at all	User is made aware of some basic operation of the building and some of the performance indicators	User is made aware of the main operations of the building and of the performance indicators. The user is empowered by involvement in some control actions	Makes the user fully aware of the building operation and greatly empowers the user to control actions	3
	10%	Innovation	No innovative elements presented	State of the art technologies, no innovative system or concept	Some concepts, systems or technologies are innovative	Use of innovative concepts, systems and technologies. Well integrated in the overall BUI	1

Figure 168: Suggestion for the overall part of an evaluation grid to be used within a competition context; in this example, 4 levels of performance are defined for each indicator [siow 2020]

7. Post Competition Research - Examples

As described in the report on the outcome of subtask B of EBC Annex 74, many teams from past competitions operate their houses after the competition as "educational living labs" located on the university home campus.

The competitions in Dubai 2018 and in Szentendre 2019 originally had the intention to allow teams to leave their houses on the competition site and to create common research. These options were made possible for the first time as the competitions took place on the grounds of research centres. For several reasons this process was not successful. The following examples illustrate the planning for upcoming post competition research.

7.1 SD Africa 2018[41]

The first Solar Decathlon in Africa took 2018 the chance for a living lab of all competition buildings on the site of the Research Institute for Solar Energy and New Energies located in Rabat, Morocco (IRESEN).[42] IRESEN intended by organizing the event to translate the will of the Moroccan government to reach high levels of sustainability in its energy sector. The aim of the national energy strategy is to raise the share of renewables in the national installed power capacity to 52% and reduce the electric energy consumption by 20% by 2030. The objectives through the competition were to provide a solid platform for empowering the young generation and educating the broad public, to improve the energy efficiency in the buildings, to push the envelope on clean energy technologies, ensure the financial sustainability, and finally, to unveil the perks of local raw materials.

The "SDA platform village" serves as platform dedicated to experimentation, training and research. It is built on the vision to innovate and develop the fields of green buildings, energy efficiency and smart grids as a part of the Green & Smart Building Park (GSBP) research platform. The aim is to create the ecosystem required in the development of the sustainable Moroccan and African city. This is an aim which will be achieved through the integration of renewable energies and the digitisation of the building's components, in order to enrich the capacities of the housing sector.

The Green & Smart Building Park is the place to assemble the resources and the tools, while consolidating the efforts of different institutions and local actors in the housing and urbanism sectors such as research centres, universities, development agencies, SMEs. The platform aspires to invest in the Moroccan human capital by encouraging applied research, innovation, and the creation and incubation of start-ups.

While rejoicing the success and the outcome of this African edition of solar decathlon, its legacy will live on through diverse established collaborations and initiatives in order to be in position to shape the decisions of education, engineering and scientific research.

- Joint partnerships with the academic institutions, particularly with those which have participated in SDA, in order to pool efforts and resources of partner research institutions and form a critical mass so that to come up with innovative and efficient solutions in sustainable materials and active solar technologies adapted to our local climate. The living lab will be an experimental field for new technologies and a major catalyst to the start-up of new clean-energy enterprises.

- The organization of annual international summits and events on energy-efficiency and sustainable buildings. The aim is to disseminate the knowledge and the know-how on renewables to the partner

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[41] Author: Samir Idrissi Kaitouni, IRESEN

[42] http://www.iresen.org/

universities through research studies, trainings and workshops in the trades of the buildings, and to enhance the dissemination of adapted buildings-related technologies to Moroccan industries.

Through the living lab, the organizers are looking forward to building one strong community and implementing a great environment for meeting, nurturing an ecosystem that helps innovative start up communities and pooling peers from around the world with regards to collaboration while helping to consolidate our own practice in Energy Efficiency and Renewables.
The role of Green & Smart Building Park is to assemble the resources and the tools, while consolidating the efforts of different institutions and local actors in the housing and urbanism sectors such as research centres, universities, development agencies, industrials and non-profit organizations. The platform aspires to invest in the Moroccan human capital by encouraging applied research, innovation and the creation and incubation of start-ups. The indoor laboratories of the GSBP cover the entire integrated value chain of the building and city of tomorrow. These strategic pillars will be translated into R&D projects in the Moroccan context along the whole value chain: Basic Research, Applied Research, full-scale prototypes, and Commercial Deployment.

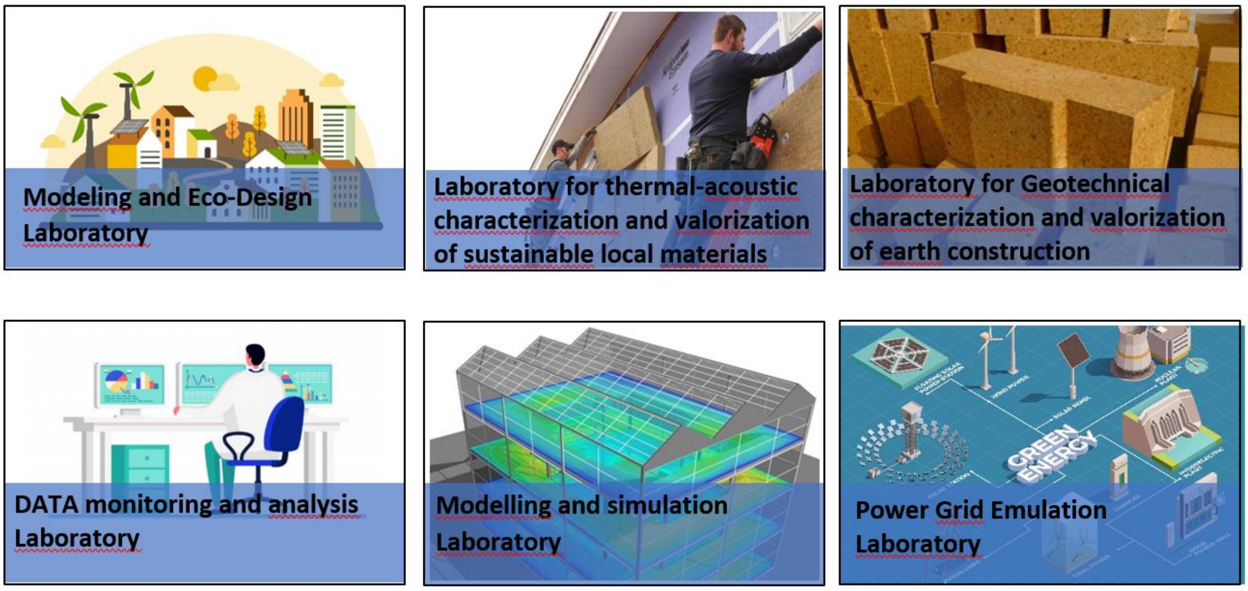

Figure 169: Research fields of the Green & Smart Building Park. Source: IRESEN

7.2 SDE 2021[43]

As the planned follow-up project to the Solar Decathlon Europe 2021, the so-called “Living Lab NRW” deals with the installation and operation of a real-world laboratory consisting of eight remaining demonstration buildings out of 18 competition entries. The demonstrators are fully functional and remain on the competition site for at least three years after the competition in order to be used for research. As partial sections of apartment buildings and as part of the ‘SDE21 Urban Edition’ in particular, the architecturally appealing demonstrators present innovative concepts for the re-densification of the city under the umbrella objectives of climate neutrality, sufficiency, resource efficiency and circular economy in the building industry, and thus offer a wide range of research potential. The outstanding location in the immediate vicinity of the city Wuppertal, enables both an optimal research and pubic accessibility. The site offers ideal

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[43] Author: Katharina Simon, University Wuppertal

conditions for creating an innovative central research and educational facility of the densely populated region North Rhine-Westphalia (NRW): The Living Lab NRW.

The Living Lab NRW offers the unique opportunity to build a network among universities in North Rhine-Westphalia and to conduct joint research within the framework of a research centre, while self-financed research beyond NRW is also welcome. The infrastructure created as well as the state-of-the-art measurement technology and equipment available provide the ideal prerequisites for this. Through the Living Lab NRW, it is possible to carry out measurements and analyses of high relevance for both research and teaching over a longer period of time and under real-world laboratory conditions. Towards this end, well-documented planning documents and results of the SDE21 competition can also partly be used. Since one of the demonstrators will also accommodate an office space and the others can be used for temporary research-related residential purposes, they can be used – depending on the research in question – both as a workplace or to investigate inhabited scenarios (e.g. user behaviour, user acceptance, etc.). Furthermore, cross-sectional analyses and comparisons of the eight demonstrators are possible and desirable. The possible research topics are manifold and their selection will fall to the universities participating in the collaborative research centre. The integration and embedment of the Living Lab NRW within the field of academic teaching also offers a great deal of potential. Applied seminars as well as topic-related final theses enable a practice-oriented education.

The Living Lab NRW project enables the establishment and operation of an NRW- and Germany-wide network for teaching and research, creates a practice-oriented teaching and learning location for pupils, trainees and students and offers innovative climate-friendly demonstration objects for the general public.

Figure 170: Site plan for the Living Lab NRW with 8 houses from SDE21 remaining for research, education and public information. Source: University Wuppertal

8. Outlook[44]

This report, together with the three complementary focus reports, collects valuable information on past competitions, with a focus on the Solar Decathlon and namely its European editions. With the online building competition knowledge platform, it makes the information is made publicly available for a wide audience. It specially addresses future organizers of building energy competitions for students.

The SDE 21/22 in Germany will be the first Solar Decathlon being able to benefit from the Annex 74 output, namely subtask A. Its main profiling was done by adding a design challenge to the demonstration unit task.

The design challenge defined as a typical urban densification task creates a real context for all of the demonstration units. In SDE 21/22, context is a main issue to better position the competition in the architectural debate, and it allows the consideration of adjacent urban layer aspects such as mobility. The common urban context, including the focus on further construction and use of the existing building stock, reflects main key European requests.

All-electric homes as demonstrated in all SD Competitions to date are just one of the options to reduce climate emissions of buildings. It is a precondition that the power used is mainly based on renewables. Urban options for the transformation of the building stock to climate neutrality might be different and based on a mix of energy systems and sources such as green district heat/cold, biogas, green hydrogen etc. Future organisers will need to align a competition to local and regional conditions.

One issue that urbanisation brings is the affordability of living space. The focus should not lie just on technical prowess or design aesthetics, but should also demonstrate affordable solutions for the general public to fully cover the social dimension of an urban transformation to climate neutrality.

Working with performance simulation tools for energy, indoor climate, lighting, life cycle assessment, circularity, etc. in the early design phase, stimulates the buildings' design proposals, and avoids extra costs for adjustments in the later phases of planning and construction. Workshops, working documents, and common tools may be considered to raise the overall level in this field of work. The focus report with its set of topical papers also may work as thematic inspiration and link to IEA research activities. Building information modelling (BIM) also serves as the state-of-the-art format for intensive documentation and linking of information over the entire life-cycle of a building. Future competitions are a very suitable testing ground for BIM application and the teaching of BIM best-practices. Student competitions are a very valuable instrument for education of future engineers and architects and should consider an up-to-date level in the use of simulation and design tools as well as information exchange platforms.

To date, the analyses of the SD energy systems have been mainly limited to the houses' energy consumption and the energy yield of the solar power systems. The considerable time and expense that goes into developing and constructing the buildings raises the question of an advanced monitoring concept. The post processing of the SDE 21/22 results will show, how successful research and competition are compatible. The established living labs with buildings remaining on former competition sites give the floor open the dialogue for future research and more the continued benefits from the large efforts teams' who have been dedicated their energies spent onto the design and construction of innovative demonstration houses.

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[44] author: Karsten Voss, University Wuppertal

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List of SDE Teams and Abbreviations

The following list refer the team abbreviations used in graphics and tables of chapter 2 and 3 to the participating universities in SDE 2010/12/14 and 2019. For more details please refer to the online knowledge platform https://building-competition.org/

ID	Team Name	Universitiy / Universities
ROS	Team IKAROS Bavaria	Hochschule Rosenheim, Germany
CEU	SMLhouse	Universidad CEU Cardenal Herrera, CEU-UCH Team Valencia
TUC	Sunflower	Tianjin University China
BER	Living Equia	University of Applied Science for Technologie and Economics Berlin, Beuth Hochschule Berlin, University of Arts Berlin, Germany
VGT	LumenHAUS	Virginia Polytechnic Institute & State University, United States of America
UDV	Urcomante	Universidad de Valladolid Spain
HFT	Home+	HFT Stuttgart, Germany
UON	Nottingham HOUSE	University of Nottingham
AMP	Napevomo	Paris Tech, France
HUT	Luuku House	Aalto University, Helsinki, Finland
IAA	FabLab House	Instituto de Architectura Avanzada de Catalunya, Spain
BUW	Team Wuppertal	Bergische Universität Wuppertal, Germany
UPC	LOW3	Universidad Politecnica de Catalunya Spain
UDS	Solarkit	Universidad de Sevilla Spain
TUS	Bamboo House	Tongji University Shanghai, China
GRE	Armadillo Box	Ecole Nationale Superieure d Architecture de Grenoble, France
UOF	RE:FOCUS	University of Floida, United States of America
PLT	Plateau Team Universidad de Alealá	Universidad de Castilla & la Mancha Universidad de Alcala de Henares University
REC	Team Reciprocite	Universite d Ángers& Appalachian State University
DTU	Team-DTU	Technical University of Denmark
TEC	TEC Team San José	Costa Rica Institute of Technology
ROM	DenCity	Universita degli studi di Roma TRE, Italy
LUC	Team Lucerne	Hochschule Luzern & Hochschule Zentralschweiz
BUC	Team EFdeN	Technical University of civil Engineering Bucharest, University Politechnica Bucharest, ION MINCU University of Architecture and Urbanism
DEL	Prêt-à-Loger	Delft University of Technology, The Netherlands
ROF	Team Roof Top	UdK Berlin, TU Berlin, Germany
SHU	Team Shunya	Academy of Architecture Indian Institute of Technology
OTP	Team On Top	University of Applied Sciences Frankfurt
BAR	Team Resso	Universitat Politecnica de Catalunya Escola Tecnica Superior Dárquitectura del Valles
UNI	Team Unicode	National Chiao Tung University
CUJ	Chiba University	Chiba University Japan
FNX	Team Fenix	Universite de la Rochelle & Universidad Tecnica Federico Santa Maria

ID	Team Name	Universitiy / Universities
INS	Team Inside Out	Rhode Island School of Design & Brown University &University of Applied Sciences – Erfurt
MEX	Team Mexico Unam	Universidad Nacional Autonoma de México & the Center of Research in Industrial Design and the School of Engineering & the School of Arts
PAR	Team Paris	ENSA PARIS MALAQUAIS / ESIEE PARIS / ESTP PARIS / CHIMIE PARISTECH ENSG / UNIVERSITÉ PARIS EST
KMU	KMUTT-Team	King Mongkut's University of Technology Thonburi
DTU	Team DTU	Technical University of Denmark, Denmark
TJU	Tongji Team	Tongji University, China
UPC	(E)CO Team	Universitat Politècnica de Catalunya, Spain
CUJ	Chiba University	Chiba University, Japan
CEU	CEU Team Valencia	Universidad CEU Cardenal Herrera, Spain
ABC	Team ABC	Bordeaux University, France
FAU	Cem+nem-	Universidade do Porto, Portugal_CEM´
RWT	CounterEntropy	RWTH Aachen University
AND	Andalucia Team	Universidades de Sevilla&Jaén&Málaga, Spain
BRA	Team Brasil	Universidade Federal de Santa Catarina& Universidade de Sâo Paulo, Brasil
BME	Odoo Project	Budapest University of Technology & Economics, Hungary
BUC	Prispa	University of Architecture and Urbanism&Technical University of Civil Engineering of Bucharest&University Politehnica of Bucharest
ROM	Med in Italy	Universitá degli Studi di Roma TRE&Sapienza Universitá di Roma& free University of Bozen & Fraunhofer Italy
STS	estonyshine	École Nationale Supérieure D´Achitecture Paris-Malaquais& École des Ponts ParisTech& Universitá di Ferrara& Politecnico di Bari
HTW	Ecolar	University of Applied Sciences Konstanz, Germany
UDZ	Grupo pi Unizar	Universidad de Zaragoza,Spain
TRA	Canopea	École Nationale Supérieure D´Architecture de Grenoble
EHU	EHU Team	Universidad del País Vasco (Euskel Herriko Unibertsitatea), Spain
ATL	Atlantic Challenge	École Nationale Supérieure d'Architecture nantes, École Centrale de Nante, Ecole Supérieure du Bois
TUB		Technical University of Civil Engineering Bucharest, Romania
BUD		Budapest University of Technology and Economics, Hungary
UPC		Universidad Politécnica Catalunya, Spain
DEF		Delft University of Technology, Netherlands
GUB		Ghent University, Belgium
PLF		Ecole Nationale Supérieure d’Architecture et de Paysage de Lille, France
MIH	SOMESHINE TEAM	University of Pécs (Hungary), University of Miskolc, University of Blida (Algerie)
SEV		Universidad de Sevilla, Spain
KMU		King Mongkut’s University of Technology Thonburi, Thailand
VAL		Universitat Politècnica de València, Spain

ANNEX 74

EBC

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