ANNEX 74

EBC
Energy in Building and Communities Programme

International Energy Agency

Competition and Living Lab Platform (Annex 74) Science & Technology (Subtask A) Focus Report 2: Topical Paper

November 2021

ANNEX 74

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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 (*)
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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 (*)
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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

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1. Introduction

Sebastian Herkel, Fraunhofer Institute for Solar Energy Systems ISE, Germany

Objectives

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 this 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. In the case of modular construction and sustainability in construction the main source was an in-depth technical analysis of former editions of the Solar Decathlon, mainly the European edition.

Contents of the topical paper report

In the following chapters an insight into different aspect of the building design and different technologies are given. This comprises design and building envelope related aspect like comfort and air. Conceptual and methodological approaches like modular buildings and sustainability in construction are described as well. The following areas are addressed:

- thermal comfort
- air tightness
- modular and prefabricated construction
- sustainable and recyclable construction

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.[1] In addition, an in depth insight into energy flexibility and the human-machine interaction the field of operation and control is given:

- heat pumps
- solar thermal systems
- photovoltaic
- hybrid solar systems
- batteries
- energy flexibility
- user friendliness

Starting with a general overview, parameters and key performance indicators are described as well as simulation, monitoring procedures and analyzing methods. Further readings are given to those, who like to deepen their knowledge giving an easier access to relevant publications.

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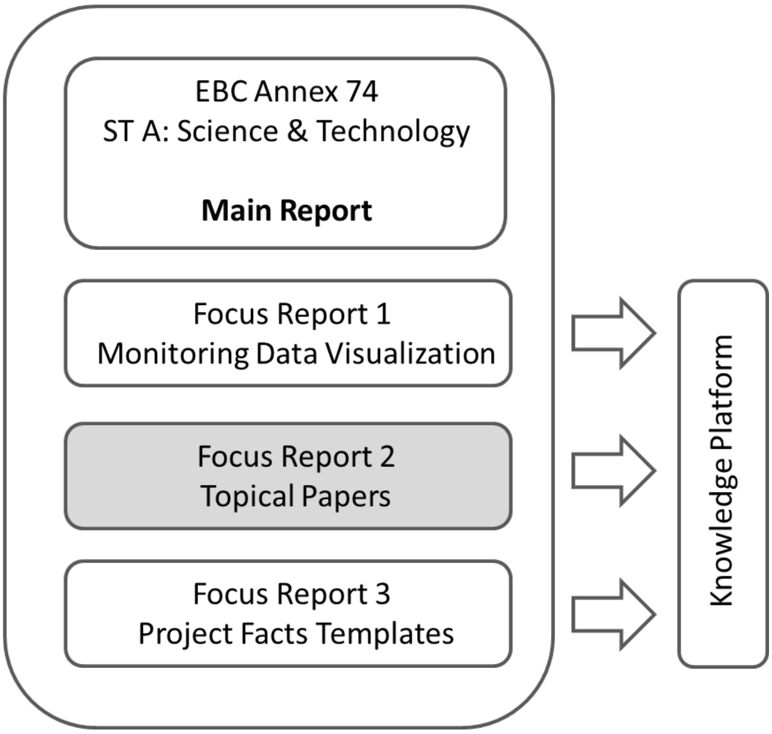
[1] IEA DHC: www.iea-dhc.org, IEA HPT: https://heatpumpingtechnologies.org, IEA EBC: www.iea-ebc.org; IEA SHC www.iea-shc.org

The set of papers presented within this are as well published online on the knowledge platform building-competition.org [2]

The Annex 74 „Competition and Living Lab Platform“ runs between January 2018 und June 2021 within the Energy in Buildings an Communities Technology Collaboration Programme (EBC) of the International Energy Agency[3]. 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 the link to expertise from previous and current IEA activities[4]. 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 is The Focus Report



Structure of the documents generated by subtask A

2 https://building-competition.org/material/show/TOPA
[3] https://annex74.iea-ebc.org/

[4] www.building-competition.org

2. Comfort

Prof. Dr. Karsten Voss, University Wuppertal, Germany

2.1 General Relevance

Maintaining indoor comfort that meets the occupant's expectations is one of the major efforts in building design, construction and operation. The reason is, that in most locations in the world, the typical outdoor conditions are more or less far from thermal comfort as defined in typical comfort standards such as ISO EN DIN 7730 (air conditioned buildings, [1]) or EN DIN 15251/ASHRAE 55 (adaptive thermal comfort, non air-conditioned buildings [2], [3]). On the other hand, expectations of peoples are changing. Example are the rising need for cooling due to increased income in the fast economic growing countries of the world and the introduction of air conditioning as standard in private cars. It is a current major task to reduce energy use in buildings while at the same time providing comfortable indoor environments for the occupants (EBC Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings).

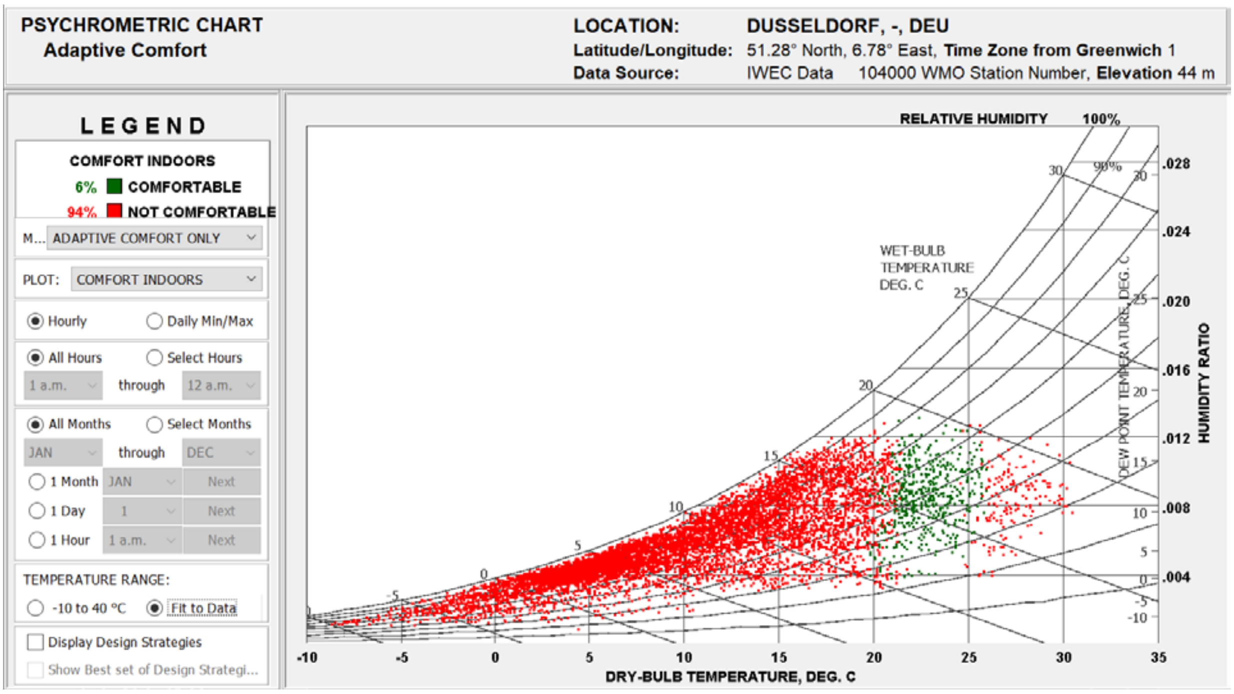


Figure 2-1: Example of a climate analysis with respect to thermal comfort. For this example (Duesseldorf, Germany) only 6% of the annual hours provide comfort conditions according to the adaptive thermal comfort approach. Source: Climate Consult tool.

In most climates, the (operative) temperature is in the focus of thermal comfort. The relative humidity gains importance in connection with high temperatures (e.g. Singapore) as the evaporative cooling of the human body becomes more and more limited (>60%). In heating conditions, unfavorable low humidity (<30%) may occur due to the drying of ambient air by the temperature increase.

Air quality with regards to human activities in buildings is typically addressed with CO_2-concentration analysis. The topic has a major relevance in the discussion on low energy buildings due to increased air tightness of building envelopes and the performance of fan assisted ventilation systems. CO_2-concentrations are also affected by the occupation density of buildings. Volatile Organic Compounds (VOC) are another

issue of indoor air quality but mainly a topic for new constructions and new materials or paints used for internal cladding or furniture in building renovation. Concentrations are usually far from critical and decreasing fast, as long as material selection has been done carefully.
Focusing on visual comfort in residential buildings (no constant computer workplace conditions) the main issue is the visual contact from interior to exterior, especially in summer conditions with shading systems active. Keeping the indoor temperature within the comfort limits should be possible without blocked view. Today's national and international standards don't cover this issue. Minimum illuminance levels are an issue for non-residential buildings only.

2.2 Relevance in Building Competitions & Living Labs

Typically, teams in building energy competitions address thermal comfort in the planning by dynamic simulation tools with a wide range of complexity and accuracy. No standard tool was provided in the SD up to now, but standardized simulation input reports have to be delivered. Output reports have not been standardized up to now. In the 2014 SDE the organizers simulate all buildings with an identical tool additionally [4].
Comfort is always addressed in an own discipline within the SD. It was mostly associated with a maximum of 100 points (of 1,000) and always fully based on monitoring data. Comfort monitoring was performed in SDE2010 and 2012 with tripod mounted sensors, 1.5 m above the floor with a resolution of 1 minute and 15 minutes averaging before storing the data [5]. Air temperature sensors were shielded and actively ventilated by a micro fan to avoid radiation influence. Typically, two sections or rooms were observed per house (bedroom, living room). Starting in 2014 comfort in SDE is evaluated according to the adaptive thermal comfort model.
In SDME2018 operative temperatures were measured at two locations with globe thermometers and data with 1 min resolution were provided [5]. Fixed limits for temperatures have to be kept (22-25°C) as buildings have been fully air-conditioned (no adaptive thermal comfort approach).
In SDE 2010/12 air quality was measured in the form of continuous CO_2 monitoring in combination with one of the tripods for thermal comfort evaluation. VOC measurements were performed separately on one competition day. A light sensor was placed on the work space desk in each house to detect the illuminance level continuously. Visual contact was not part of the investigation up to now.
In none of the competition's user satisfaction was evaluated. Only monitored comfort was addressed. Living labs in general allow to address this issue as buildings are occupied and questionnaires can be applied for user centered research.

2.3 Parameters

There are a big number of parameters influencing indoor comfort. Beside the ambient climate, the building design and its construction quality the user behavior are in the center of interest. Increasing ambient temperatures due to the predicted climate change are to be considered for new designs as well for the retrofit of buildings.

2.3.1 Performance Indicators

Indoor comfort is mostly qualified on the level of performance classes. Performance classes are defined by the relevant standards such as ISO EN DIN 7730 or EN DIN 15251/ASHRAE 55. Simulated or measured data can be analyzed against performance class boundaries and times of consistency with classes can be cumulated. The analysis centers on the times of occupation, as indoor comfort is not a relevant topic in unoccupied situation (e.g. nights or weekends in office buildings).

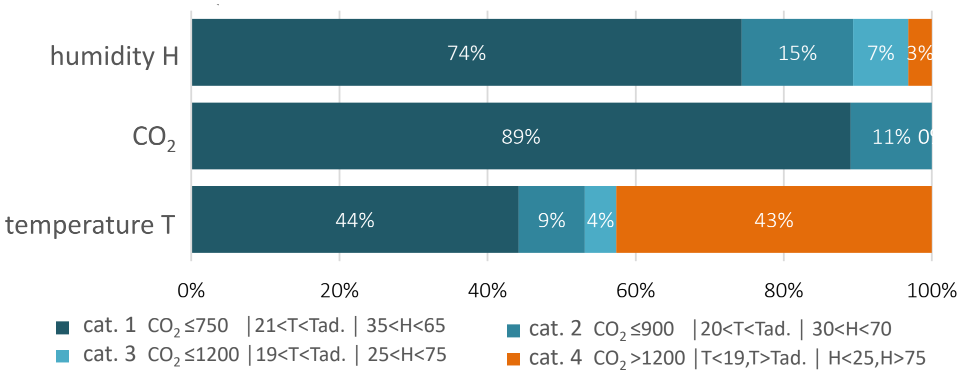


Figure 2-2: Example of a performance class analysis by simulations for temperature and air quality according to EN DIN 15251. Data address a full year, but occupation times only. Source: SimRoom, https://ingefo.de/Werkzeuge/Sim-Room/

2.4 Simulation

Simulation of indoor comfort needs fully dynamic building simulation programs with minimum hourly time resolution (Wufi, TRNSYS, IDA ICE, ….). Information on phenomena such as the temperature stratification in a room is provided by CFD calculations (Fluent,…) but typically not dynamically calculated for a full year analysis.
Most building simulation tools provide information on air temperatures and operative temperatures as well but mostly as values per zone (fully mixed air). The calculation of the operative temperature as a function of the place in a room needs a geometrical model to investigate view factors for all surfaces, relative to the point of interest. In the case of humidity- and CO_2-concentration, the models need extended algorithms and input data for time dependent humidity and CO_2-sources (people, plants, showers…) in the rooms or zones. Internal heat gains and user behavior with respect to occupancy, window ventilation and blind control are important factors to describe the thermal phenomena. Practically all these information’s are not easy to receive for occupied buildings and tackle the field of information privacy. A further issue in many cases is the unknown infiltration rate of a building in real operation.
The use of monitored weather data of the same time resolution is essential when simulation results are to be compared to measurements. Critical aspects are the influence of external shading and the algorithms for the solar radiation calculation on the various building surfaces based on global radiation measurements only. Better results are achieved with irradiation data separated in the direct and diffuse component.

2.5 Monitoring

Typically monitoring is performed with sensors for temperature and humidity combined and sometimes added by an air quality sensor (indoor climate station). Beside sensors for the scientific market more and more equipment on the consumer level shows up with suitable quality (Netatmo, IC meter,…). Adding air quality sensing mostly creates the need for active power supply and wiring to an AC plug due to increased power consumption.

2.5.1 Temperature

Typical sensors are resistance thermometers (PT100, PT1000, …) or thermocouples (NiCrNi, …) hard-wired to a data logger or central data acquisition system or wireless connected to a cloud service. The advantage of thermocouples is the smaller construction with less surface to absorb solar radiation and less thermal mass. Typical installations for the air temperature shield the sensor from direct radiation and/or actively ventilate the sensor surrounding, whereas the operative temperature is measured by globe thermometers in the form of a black sphere of about 15 cm diameter, non-vented. Compromises e.g. for the purpose of building automation apply wall mounted sensors build into small plastic boxes (installation boxes) with openings for passive ventilation. These sensors measure a mixture of air and operative temperature due to the effect of the thermal mass of the wall. Whereas simulation programs (except CFD tools) deliver a single temperature per room (refer above) the reality shows more or less differences with respect to room height (stratification) or room depth (distance from façade). These differences have to be carefully considered when comparing simulation and monitoring results.

2.5.2 Humidity

Many aspects are equal to those mentioned for the temperature measurement. The air temperate surrounding the humidity sensor influences the relative humidity reading as due to the changing carrying capacity with temperature. Typical sensors use the change of the electric capacity and provide an electric signal in the form of 4-20 mA or 0-10 VDV for 0 to 100% relative humidity. Generally, the accuracy is not as high as a temperature measurement and more sensitive to sensor costs. A resolution lower than 5 minutes doesn´t make sense for most sensor types due to their reaction time.

2.5.3 CO_2

Sensing the CO_2-concentration is currently shifting from the scientific to the consumer market. Most sensors apply the IR-Absorption method to detect concentrations in the range from 200 to 5,000 ppm. Typically, sensors automatically recalibrate themselves based on the knowledge that outdoor concentrations are about 400 ppm and more or less constant.

2.5.4 Visual Contact

Monitoring of blind positions is a very complex task as more than the status “closed” and “opened” is relevant for most moveable shading devices. This creates the need for position sensing and in cases of venetian blinds the sensing of the slat angles. In general, this is possible in the case of “smart controls” with additional logging of the signal. Another approach is based on watching a façade with a camera (indoor or outdoor mounted) and apply automated image post processing. In the case of camera systems, especially when indoor mounted) occupant’s privacy is heavily affected.

2.6 Post Processing of Results from Simulation & Monitoring

Simulation and monitoring deliver a large number of data, especially when long time series are stored in high resolution. High resolution is a critical factor to capture user behavior (window opening …) and indoor comfort peaks. High quality visual post processing of data allows quick general performance view. The examples below describe typical outputs here as graphical outputs of the simulation tool “SimRoom” (Figure 2-3 to Figure 2-6). A performance view in the form of a compact calcification graph is already presented with Figure 2-2.

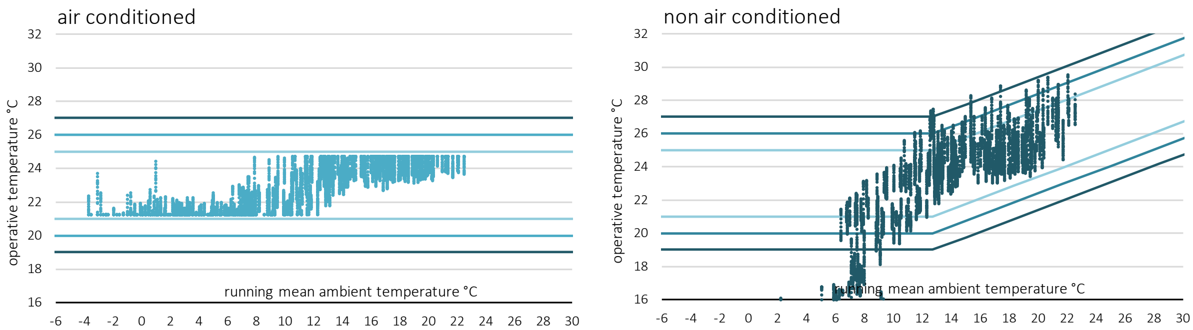


Figure 2-3: Analysis of the operative temperature during occupation of a room during a full year. SimRoom results. The right diagram shows the non-conditioned situation, in the left diagram heating and cooling was active during simulation (21°C, 25°C).

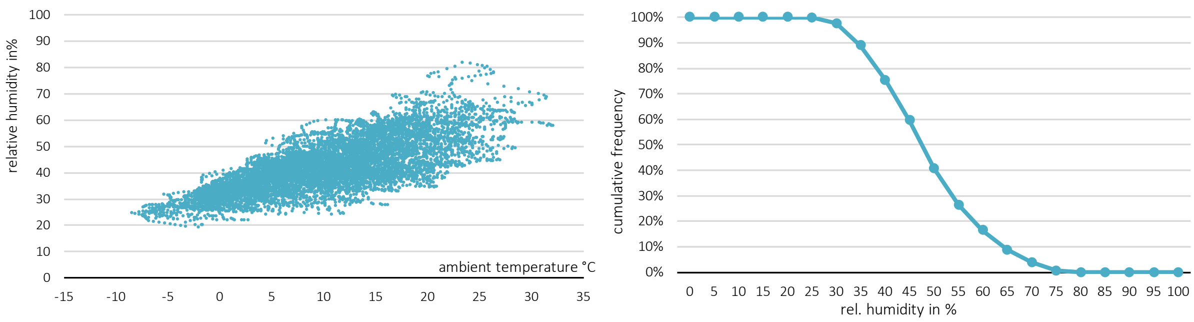


Figure 2-4:Analysis of the relative humidity during occupation of a conditioned (heating & cooling) room during a full year. SimRoom results. The left diagram illustrates the relative humidity as a function of ambient temperature, the right diagram the correlated frequency distribution.

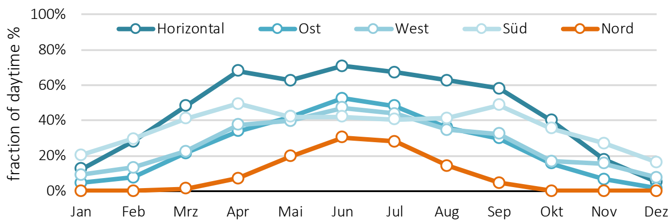


Figure 2-5: Analysis of the monthly activation time of moveable sun-shading devices based on indoor and outdoor climate as well the radiation and temperature based control algorithm. SimRoom results.

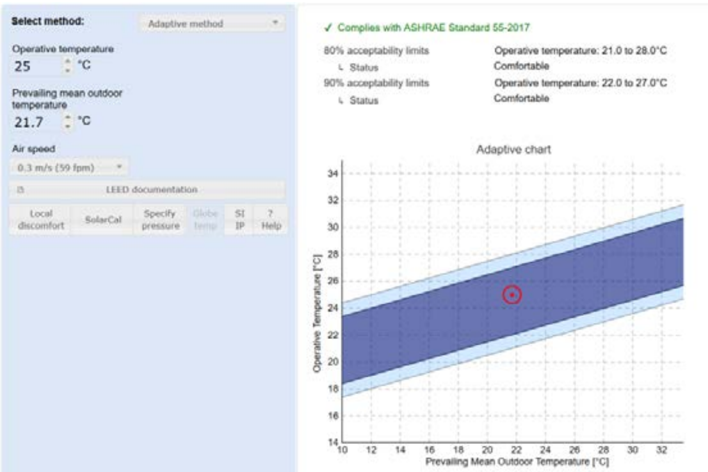


Figure 2-6: Analysis of the thermal comfort based on measurement or simulation data uploaded in a web based tool. http://comfort.cbe.berkeley.edu/

2.7 Further Reading

[1] ISO EN DIN 7730: Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, 2006-05

[2] EN DIN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 2012-12

[3] ASHRAE 55: Thermal environmental conditions for human occupancy, 2017

[4] Competition Rules & Building Code SDE 2014, version 5, page 40.

[5] Vega, Sergio: Monitoring Processes of the Spanish Competitions Solar decathlon Europe 2010-12, UPM, internal report of IEA EBC Annex 74, May 2018

[6] Competition Rules & Building Code SDME 2018, version 2.0

[7] SDME Monitoring Panel – Sensors and Meters configuration, TUEV Rheinland, 2018-07

3. Air Tightness

Prof. Nathan Van Den Bossche, Ghent University, Belgium

3.1 General Relevance

The airtightness of a building reduces the air flows through the building envelope from outside to the inside (infiltration) and vice versa (exfiltration). During the heating period, the cold outside air can enter the building because of these air flows and needs to be heated. Similarly, the warm indoor air that escapes through several joints, cracks and porous surfaces is accompanied by a certain energy loss. Likewise during the cooling season the infiltration of hot outside air to the interior increases the cooling load of an air-conditioned building. This energy loss due to infiltration and exfiltration is not negligible – certainly in case of energy-efficient buildings – and must therefore absolutely be taken into account when analyzing the energy balance of a building. After all, it makes little sense to increase the insulation thickness without paying attention to the airtightness. The same is the case with introducing highly efficient ventilation heat recovery systems. Without improved airtightness, ventilation losses through the envelope become the major ventilation heat loss.

Additionally the in-/exfiltration can be detrimental for the hygrothermal performance of the building envelope and the indoor climate. In case of airtightness defects, in particular in light structures, warm and humid air may end up on the cold side of the insulation under influence of convection movements. This phenomenon can lead to internal condensation, which can damage the insulation and impair the functionality of the envelope. Furthermore the airtightness influences the acoustic quality (noise protection) and the risk of draft. Hence, it plays an important role in achieving a pleasant comfort for residents and users of a building. Unintended air exchange increases the heat load resulting in uncomfortable dry indoor air in winter (humidity < 30%). Also certain fire safety aspects are directly related to the airtightness of a structure.

3.2 Relevance in Building Competitions & Living Labs

Taking the example of the Solar Decathlon the airtightness influences the results of the competition. Based on the rules from SDE 2019 (version 2.0) the airtightness will influence the number of points reached in the comfort conditions contest (max 100) as the indoor temperature & humidity, the air quality and the sound insulation will be quantified by measurement. Indirectly the air tightness level influences the building energy consumption and the correlated contest results.

Blower door tests are part of the current SDE19 competition rules and have been performed in competitions before as part of the building performance checks.

Co-heating tests with dynamic outdoor conditions represent an advanced performance check procedure resulting in an overall envelope performance indicator, not characterizing the airtightness explicitly.

Considering and testing the air tightness teaches student teams to understand the needs and criteria for energy efficient building envelopes in the design as well as the construction phase.

3.3 Parameters

The level of airtightness is a global performance of the building envelope and depends on numerous levels and factors, such as the design of the building, the choice of materials and components, the design and execution of the construction details, the position of cables and ducts, the number of penetrations, etc. Almost all craftsmen who are successively employed at the construction site can affect the airtightness in a positive or negative way. Hence, a proper follow-up of the airtightness throughout the entire construction process, from design to execution and final inspection, is essential.

3.4 Performance indicators

The airtightness of a building can be expressed in different ways according to the ISO 9972:2015. Generally a reference pressure difference between the indoor and outdoor environment of 50 Pa is assumed, although other reference values can also be used (e.g. 4 Pa or 10 Pa). The leakage rate that infiltrates through the building envelope at this pressure difference, usually determined by a pressurization test, represents the sum of all leaks through the building envelope. The total air leakage rate at the reference pressure difference Δp_r is noted as $\dot{V}_{\Delta pr}$ and is expressed in m³/h.
To normalize this value to the size of a building, the air change rate $n_{\Delta pr}$ is introduced. This value is expressed in h^{-1} and calculated by dividing the mean air leakage rate at the reference pressure difference Δp_r by the internal volume V. The air change rate is a good criterion for the overall airtightness performance of a building. Alternative quantities that characterize a specific execution quality are the air permeability $q_{\Delta pr}$, by dividing $\dot{V}_{\Delta pr}$ by the envelope area A_E, (using overall internal dimensions), and the specific leakage rate $w_{\Delta pr}$, calculated by division of $\dot{V}_{\Delta pr}$ by the net floor area A_F. The last two quantities are both expressed in m³/(h.m²) and are independent of the size and compactness of the building. They are normally applied for large buildings. These terms are usually noted as $\dot{V}_{50}$, n_{50}, q_{50} and w_{50}, i.e. for the most common reference pressure difference across the building envelope of 50 Pa.
Except for the pressurization test, a pressure difference of 50 Pa between the indoor and outdoor environment only occurs exceptionally due to strong winds; the pressure difference between the inside and outside will usually be a lot lower than this value. Thus the average infiltration rate n_{inf} that really occurs as a result of deficiencies of the buildings airtightness will be much lower than the infiltration rate that would result from an artificial pressure difference of 50 Pa. Estimating the infiltration rate out of the empirically determined air change rate differs from country to country. It can be estimated by multiplying the n_{50} value by a factor that varies between 0.03 and 0.1, depending on the building type, its height and its exposure to the wind. A typical average value is 0.05. The resulting infiltration rate can be used to calculate the impact of the heat losses caused by infiltration on the energy use of a building via the equation $\varphi_{inf} = 0.34 * n_{inf} * V * \Delta\theta$, according to ISO 52016-1:2017 [ISO52016].

3.5 Simulation

In contrast to e.g. the performance of thermal insulation, the airtightness of a building cannot be calculated or accurately be predicted in the design phase. Aggregating data on component level, e.g. the porosity of a material, only provides a lower limit which is typically exceeded due to installation deficiencies at joints and cracks. Consequently, the airtightness can only be determined after the execution phase using a pressurization test.
In order to simulate the impact of airtightness on the air change rates in a building, a distribution of air flow cracks is typically modeled in an airflow network model. Often, one crack accounts for a certain area of a wall element. Due to the fluctuating pressure difference over the crack, the airflow through the crack varies. The parameters of the crack can be adapted to match the values found by the pressurization test. A well-known tool for airflow simulations is CONTAM, developed by the National Institute for Standardization and Technologies (NIST, US). Other possible softwares / tools for multizone air flow modelling are TRNflow (Transsolar Energietechnik GmbH, Germany), COMIS (IEA Annex 23), etc. [TRNFLOW], [COMIS].

3.6 Monitoring

The airtightness of a building can be measured with a pressurization test, also called an infiltrometric test or blower-door test. It is used for locating and correcting air leaks, as on orienting measurement during the works and as an ‘official’ measurement in order to be valorized in the context of the applicable regulations. The measurement method is described in ISO 9972:2015, replacing EN 13829:2001 and ISO 9972:2006 [ISO9972]. It consists of successively placing the building in over- and under pressure relative to the outside environment using a fan installed in an external opening (e.g. the front door or a window). The air flow rates of the fan required to ensure the different pressure levels within the building are measured at the fan. This corresponds to the total flow that penetrates through the leaks in the building envelope. The correlation between the air leakage rate and the induced pressure difference is expressed using an air leakage coefficient C_L and an air flow exponent n in the equation $\dot{V}_L = C_L*(\Delta p)^n$. The total air leakage rate at the reference pressure difference is calculated as the average of the measured values for the pressurization and depressurization test.
The standard also makes a distinction in the way in which the openings that were intentionally made in the building envelope must be treated: some openings need to be closed (e.g. exterior doors, windows), others must be taped (e.g. the openings of a mechanical ventilation system) and some cannot be sealed (e.g. fixed grilles for the supply of combustion air). See standard ISO 9972 for more details.
The execution of a pressurization test can be combined with the detection of air leaks. When there is an under pressure in the building, outside air can penetrate to the interior through all openings in the building envelope. These infiltrations can be traced with the help of smoke sticks, which make the air flows visible, with an anemometer to measure air velocity, with ultrasonic leak detectors or with soap water which will form bubbles in the event of a leak. Infrared thermography can also be used to detect leaks: if there is a sufficient temperature difference between the outside and inside environment, depressurizing the building will give rise to air infiltrations which in turn can cause a local temperature change of the inner surface of the building envelope. An infrared camera can thus be used to detect the surfaces cooled by the outside air.
Alternative tests to value the infiltration rate of a building envelope are, amongst others, the pulse test of University of Nottingham and the active tracer gas methods (see ISO 12569:2017 and ISO 20485:2017), [ISO12569].
For passive houses the n_{50} value should be below 0.6 h^{-1}. Countries with cold climates typically have more airtight constructions, and this performance level is often considered as standard practice. In countries with milder climates n_{50}-values of 10 h^{-1} and higher are no exception.

3.7 Post Processing of Results from Simulation & Monitoring

After a series of measurements during the blower door test, the negative and positive pressure measurements can both be showed in one diagram, showing the building leakage (air flow rate) as a function of the artificially induced building pressure. Usually there are 10 measuring points for both over- and under pressure in increments of no more than 10 Pa. By using a log-log plot, the monomial regression of the air flow equation $\dot{V}_L = C_L*(\Delta p)^n$ appears as a straight line. The air leakage rate at a reference pressure difference $\dot{V}_{\Delta pr}$ can easily be read from this logarithmic graph for the trend lines of both the pressurization and depressurization test and the total leakage rate is calculated as the average of these two values.

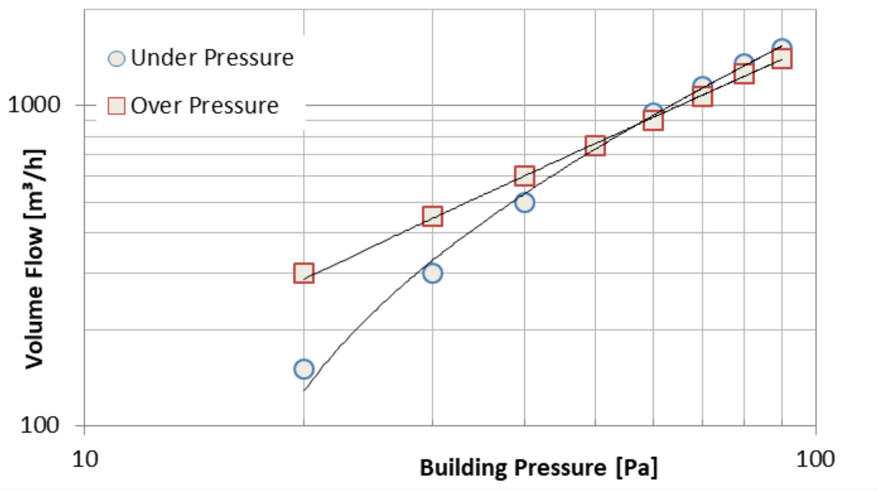


Figure 3-1: Typical graphical representation of a blower door test result. Source: S. Herkel, Fraunhofer ISE

3.8 Further Reading

[AIVC] "A guide to energy efficient ventilation", Annex 5, EBC, International Energy Agency, The Air Infiltration and Ventilation Centre, www.aivc.org

[ISO52016] ISO 52016-1:2017 Energy performance of buildings — Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads — Part 1: Calculation procedures, www.iso.org

[ISO9972] ISO 9972:2015 Thermal performance of buildings — Determination of air permeability of buildings — Fan pressurization method, www.iso.org

[ISO12569] ISO 12569:2017 Thermal performance of buildings and materials — Determination of specific airflow rate in buildings — Tracer gas dilution method, www.iso.org

[ISO20485] ISO 20485:2017 Non-destructive testing — Leak testing — Tracer gas method, www.iso.org

[TRNFLOW] TRNFlow – AIRFLOW SIMULATION IN BUILDINGS, Transsolar, https://trnsys.de/docs/trnflow/trnflow_uebersicht_en.htm (checked 26.05.2020)

[COMIS] Feustel H E, 1999, COMIS - an international multizone air-flow and contaminant transport model. LBNL - UK, Energy and Buildings, No 30, 1999, pp 3-18, https://www.aivc.org/resource/comis-international-multizone-air-flow-and-contaminant-transport-model

[CONTAM] William S. Dols, Brian J. Polidoro, CONTAM User Guide and Program Documentation Version 3.2, 2015, https://www.nist.gov/publications/contam-user-guide-and-program-documentation-version-32

4. Modular and prefabricated construction - Design and implementation strategies

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4.1 Introduction

In the construction sector, prefabricated and modular building methods have become increasingly important in recent years. The degree of prefabrication of buildings is increasing and more work steps are being shifted from the construction site to the production hall (Huss et al., 2018, S. 6). In residential construction, multi-storey buildings are increasingly being planned in timber and assembled on site in the form of room modules or flat elements, lowering the construction time on site. "We deliver in twelve weeks from the order - and not just turnkey, but ready for use. This is building 2.0. We are so fast because we plan and build the houses from a single source." (Dostert, 2018). In the German-speaking countries there are mostly small to medium-sized timber construction companies. These are mainly located in southern Germany, Austria and Switzerland. The timber construction scene in Vorarlberg plays a pioneering role. In the Scandinavian countries there is also a great tradition of timber construction and there is an increasing trend towards standardised construction methods and prefabricated buildings (Huss et al., 2018, S. 50). Alongside the advances for timber construction in housing, the Tiny House movement emerged around the turn of the millennium (Rechsteiner, 2020, S. 14). In this field the principles of small-scale living and the possibilities of scaling up and mass producing standardised micro-buildings are explored.

In the field of prefabricated construction, houses built from room modules represent the highest level of prefabrication. With this type of construction, all technical installations such as electrical wiring, heating, plumbing or air conditioning can already be installed during production. Complete prefabrication with built-in windows, pre-installed facades, kitchens and bathrooms and finished surfaces is possible with this construction method (Dörries et al., 2019, S. 13). Only the joining of the modules requires a high degree of precision and technical know-how (Jakob, 2019, S. 20). Compared to building with flat elements (wall/floor/ceiling elements), room modules are characterised by a higher degree of prefabrication. At the same time, the possibility of designing a building with very flexible floor plans decreases. This relationship is illustrated in Figure 4-1.

A major advantage of prefabrication is an integrated quality assurance during the production process (air tightness, thermal bridges, etc.), as less work takes place under outdoor weather conditions. Quality in this sense is more of an issue today than it used to be, as construction sites run at all times of the year and regardless of the season in order to keep the overall construction time as short as possible. The quality of the building physics in detail essentially determines the energy requirements of low-energy and passive houses. The advantage of modular buildings lies in the possibility of realising an extremely short construction time on site and thus also reducing construction costs (Jakob, 2019, S. 18). In addition, there is the possibility of building fully equipped and erected modules that only need to be connected to the electricity grid and the water installation. These are therefore ready-to-use buildings.

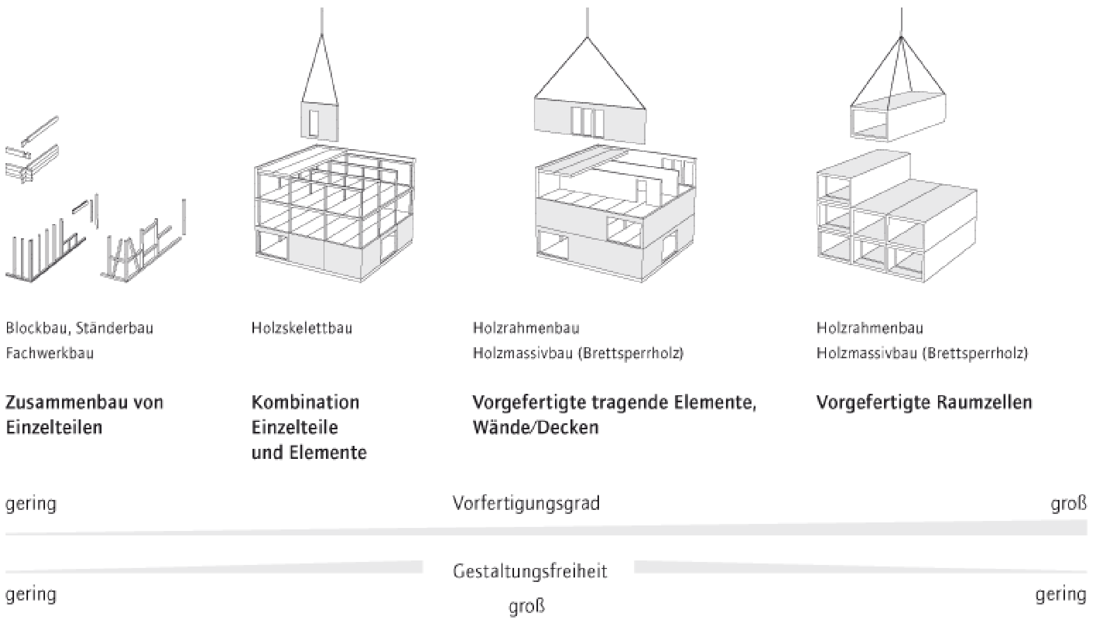


Figure 4-1: The degree of prefabrication differs depending on the chosen construction principle. Source: proHolz Austria, Zuschnitt 50 - Journal about wood as a material and works in wood (proHolz Austria, 2013)

4.1.1 Modular construction in building practice

If one looks at the share of prefabricated buildings in comparison to conventionally constructed buildings, it is noticeable that these buildings still have a comparatively low market share of approx. 16% of the total annual turnover of the construction industry in Germany (Destatis, 2020, S. 77). However, the annual survey by the Federal Statistical Office does not distinguish between elementary and modular buildings in the statistics. Only the share of timber engineering as opposed to prefabricated construction is shown separately. This means that there is still a lot of potential in the area of standardised and prefabricated construction methods. The Atlas of Multi-storey Timber Construction aptly states: "The conventional construction method appears to be less optimised compared to industrialised production. The dependence on the weather, the complex coordination of many independently commissioned trades and the per se less ergonomic working conditions on the construction site lead to inefficient processes" (Kaufmann et al., 2017, S. 142). The German government has set up a funding programme to promote this development. For example, there are funded model projects in the programme "Variowohnen" of the Zukunft Bau initiative on modular construction by the BBSR, the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR, 2017) In the programme, best-practice projects are developed and comparatively examined on the basis of common criteria.

An example of a student residence in Bochum is shown in Figure 4-2. The building was developed as a hybrid of reinforced concrete and timber construction. It consists of a reinforced concrete skeleton with suspended prefabricated concrete ceilings. The façade consists of prefabricated large-scale elements. "The exterior walls were designed as timber panel walls with a particularly high degree of prefabrication. In addition to the windows and the complete façade cladding, the necessary fixtures for the decentralised ventilation system were also already carried out at the factory." (Jakob, 2019, S. 52).

Figure 4-2: Student residence in Bochum, which was developed as a model project of the Zukunft Bau initiative. The building is constructed in elemental reinforced concrete skeleton construction with prefabricated timber panel elements. Source: ACMS Architekten GmbH, Wuppertal, © Sigurd Steinprinz, Düsseldorf (Jakob, 2019, S. 50)

As an exemplary building from the modular construction sector a hotel in Dornbirn, Austria is shown in Figure 4-3 and Figure 4-4. The project is ideal for modular construction, as this type of building has recurring room units and therefore economies of scale come into play through the production of identical modules (Kaufmann et al., 2017, S. 146). The ground floor of the building was built conventionally with reinforced concrete. The three upper floors house the 39 hotel rooms. Room modules with three different room sizes were developed for this purpose, all based on the same construction and façade structure. The room cells were completely prefabricated in the factory. This means that the façade with windows as well as the sanitary blocks and all finished surfaces, as well as the built-in furniture, were installed in the factory.

Figure 4-3: The rooms of the Hotel Katharinenhof in Dornbirn were developed as room cells and delivered to the construction site fully equipped. Source: Johannes Kaufmann Architektur, © Radon Photography (Kaufmann et al., 2017, S. 72–73)

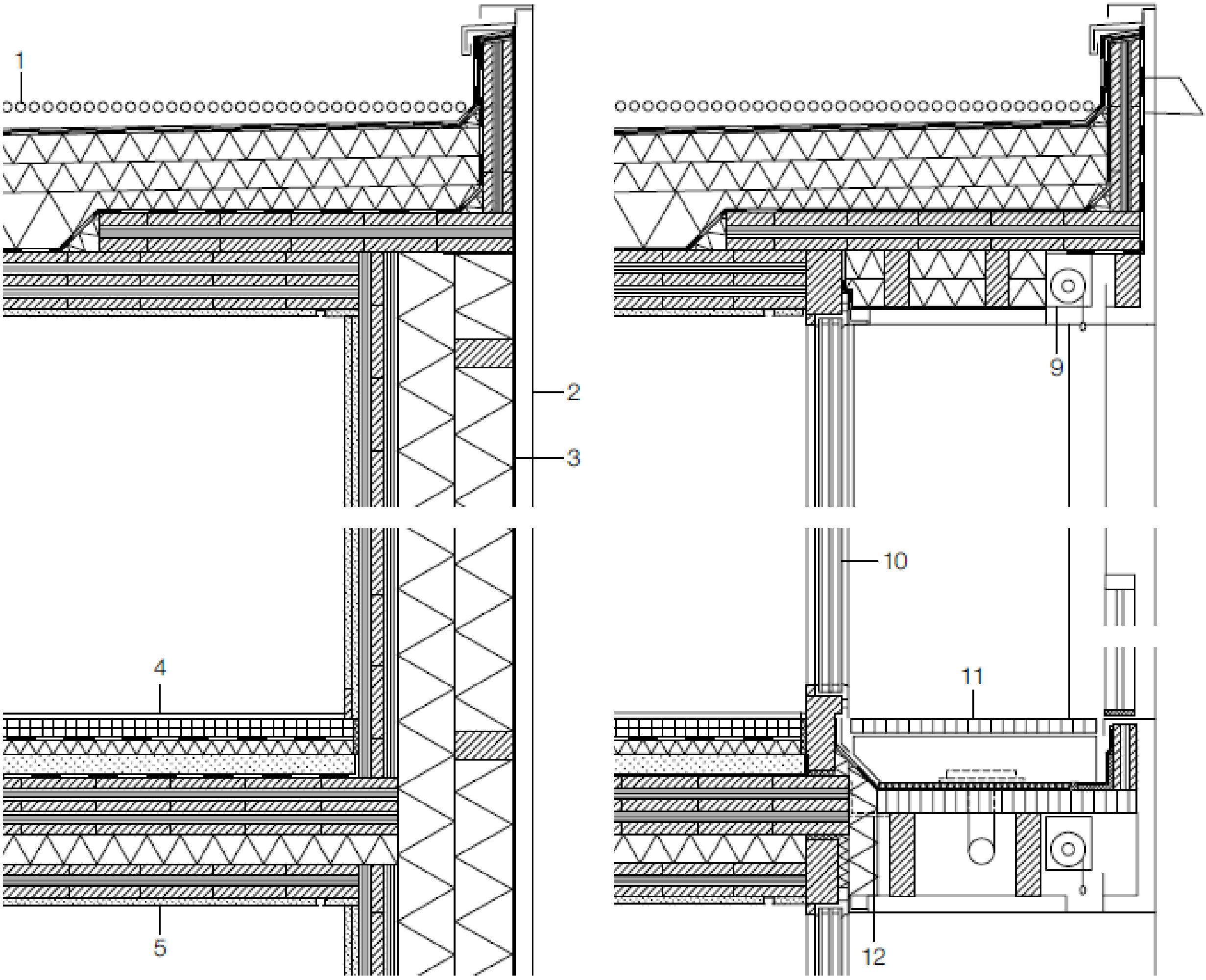


Figure 4-4: Façade section showing the module joints, visible through the doubled floor and ceiling elements at the Hotel Katharinenhof. Source: Johannes Kaufmann Architektur (Kaufmann et al., 2017, S. 73)

4.2 Modular construction and prefabrication at the Solar Decathlon Europe

The European edition of the Solar Decathlon competition, the Solar Decathlon Europe (SDE), provides the thematic framework for a comprehensive analysis. A total of 65 houses built between 2010 and 2019 will be evaluated. The projects will be examined to find out which prefabrication strategies were used by the teams. The main question is whether there have been particularly innovative solutions in the past editions, e.g. regarding the connection of the modules or elements or regarding the rapid assembly of the SDE houses on site.

The Solar Decathlon Europe poses a unique challenge to all participants in terms of speed and Just-In-Time (JIT) assembly. The precise delivery of house modules or prefabricated elements is a prerequisite to be successful in the assembly and disassembly of the event. The construction schedule for all houses (up to 9-20 houses are built in each edition) will be organised centrally. The construction site will be run by the participating students separately. About 500 to 800 students work on site at the same time. Each team has the house delivered by about 3-7 trucks and erects it with truck-mounted cranes and forklifts (see Figure 4-5). The time for assembly and disassembly is kept to a minimum. These time and space constraints mean that the houses are usually heavily prefabricated and very well thought out in relation to the building conditions on the competition site.

Figure 4-5: Assembly of a module at the SDE2014 in Versailles. Source: Solar Decathlon Europe, Jason Flakes (SDE flickr, 2014)

4.2.1 Data basis and methodology

For the cross-sectional analysis, the project documentation from the SDE 2010 and 2012 in Madrid (Spain), SDE 2014 in Versailles (France) and SDE 2019 in Szentendre (Hungary) were considered. The SDE buildings are well documented, as the participating teams develop full execution plans during their design process and also describe the construction phase in detail. As part of the research project Annex 74 - Competition and Living Lab Platform of the International Energy Agency (IEA EBC Annex 74), an online documentation platform was created, initial cross-sectional analyses were carried out and the proportion of modular or element-based buildings was determined. For further analysis, the design strategies are described in more detail and clustered.
The SDE houses are categorised in terms of prefabrication and modular construction on the basis of drawings and photos (of assembly and disassembly). The parameters considered relate to criteria ranking the projects from the overall concept to the technical details, for example innovative connection techniques. A weighted evaluation in 9 categories has been applied, with a total of 20 points to be awarded. Table 4-1 lists the categories and their respective weighting in %.

Table 4-1: Evaluation criteria with respective weighting

Type of Prefabrication	15 %
Connections	25 %
Number of Modules/Elements	30 %
Technical Core	5 %
Façade	5 %
Roof-PV	5 %
Visibility of joints	5 %
Technical Installations	5 %
Transport	5 %

This results in the degree of prefabrication with a five-point rating scale with the quantiles listed in Table 4-2 from Very Low to Very High.

Table 4-2: Rating scale with quantiles

Very low	0 – 20 %
Low	21 – 40 %
Medium	41 – 60 %
High	61 – 80 %
Very high	81 – 100 %

For the cross-sectional analysis the buildings need to be clustered according to their building specifications and construction techniques in terms of prefabrication. For the assessment of the houses, only the most relevant aspects and key characteristics have been considered. According to Table 4-1 the following definitions have been established for the nine categories of evaluation.

Type of Prefabrication

The houses are clustered into three groups. Group 1 are houses that are built up from flat elements (1 point), e.g. floor/ walls/ ceilings. Group 2 are houses that are designed with room modules (3 points). In group 3 all houses are set, which use both principles combined as hybrid (2 points).

Connections

The way in which the modules or elements are connected is assessed on the basis of their solvability. The scale ranges from ‘Glued’ (1 point), a connection that cannot be detached without destruction, to reversible ‘Plugged’ connections, which are rated best (5 points). The intermediate stages are ‘Bolted’ (4 points), ‘Screwed’ (3 points) and ‘Welded (2 points).

Number of Modules/ Elements

For the competition, a high degree of prefabrication is beneficial for the teams due to the short assembly times. A low number of elements used results in a higher degree of prefabrication. A very high number of individual elements leads to many on-site assembly steps.

Table 4-3: Overview of scoring for three of the criteria/categories

Points	Type of Prefabrication	Connections	Number of Modules/Elements
6			1-2
5		Plugged	3-4
4		Bolted	5-10
3	Modules	Screwed	11-20
2	Hybrid	Welded	21-30
1	Elements	Glued	31-40
0			> 40

Technical Core

A technical core (e.g. utility module or shaft) can be useful in order to bundle all technical functions of the house to a specific point. Especially if a team works with elements instead of room modules. Therefore, there is one point given for teams that designed a core element (1). Houses with no core receive no extra point in this category (0).

Façade

In this category it is evaluated, if the façade of the building is pre-mounted (1) or if it is non-pre-mounted (0). This design decision is important in two ways: teams can save construction time on-site, if they have already pre-mounted the façade. This is the aspect which is honoured for evaluating the degree of prefabrication. The second aspect refers to the detailing of the connecting joint in the façade. For this see point ‘Visibility of joints’.

Roof-PV

The roof-PV is evaluated in a similar way as the façade: there is one point assigned for pre-mounted (1) roof-PV and no points when there is installation on-site (0) needed for the roof-PV.

Detailing of joints

In general, there are two ways to deal with the joints of room modules or elements in the façade. The first option is to leave the joints visible in the façade, the other option is to hide the joints. The construction of the joints can be done either by using predefined fittings such as moulded parts (e.g. aluminium c-profile) or by fitting in the missing pieces of the façade on site. As the installation of façade elements on-site needs more construction labour and time, this is assessed with zero points, if no fittings (0) are used. When a team uses a predefined fitting (1) there is given one point.

Technical Installations

For the technical installations of the buildings there are two distinctions made. In case the installation of all technical building systems is made in the upfront and there is only a need to connect to the local water and electricity grid, the house is regarded as plug & play (1) and receives one point. For all other stages of installation, where more or less installation on-site (0) is needed, no points are scored for this category at all.

Transport

According to the category 'number of modules/ elements' it can be assumed for transportation that there is a correlation between transport size and the extent of prefabrication. Usually room modules are larger than flat elements or single pieces and require special transport (1). Houses that use standard transport (0) tended to have smaller and less prefabricated elements/modules and thus receive zero points in this category. This category includes some imprecision, as room modules can also be manufactured with standard transport dimensions. However, as no data was available on the number of trucks per house, only the most relevant/largest components of the houses were measured and compared.

Table 4-4: Overview of scoring for the remaining criteria/categories

Points	Technical Core	Façade	Roof-PV	Detailing of joints	Technical Installation	Transport
1	Core Element	Pre-mounted	Pre-mounted	Predefined fittings	Plug & Play	Special
0	No Core	Non-pre-mounted	Non-pre-mounted	No fittings	Installation on-site	Standard

Boundary conditions

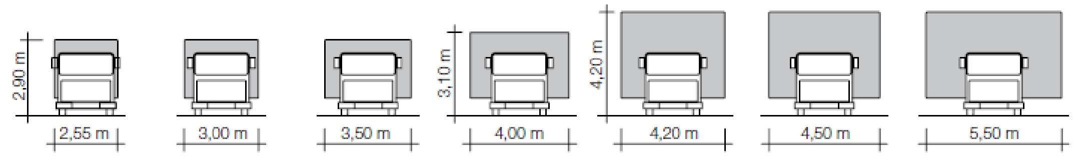
The boundary conditions are defined by the rules and regulations of the competition. With regard to the topic of prefabrication and construction logistics, the specifications for the transport of the components or modules are particularly decisive. The second important aspect lies in the time-limited assembly and disassembly phase.

Transportation requirements

During the SDE 2010 and 2012, all types of transport were allowed. During the SDE 2014, special transports were only allowed to a limited extent. In the SDE 2019, special transports were not allowed at all, which limited the design possibilities of the modules.

The following specifications were made for the SDE 2010 in Madrid: 'Every team is responsible for the transport to Madrid. They will have to consider the dimensional aspects, suggesting that the maximum load to be 'palletable'. We suggest you to contact transport companies during the development phase of the project to guarantee that the freight transport rules will be complied with. Special attention must be paid to Customs regulations by those teams not from the European Union.' As the organisers and the venue were the same in SDE2012, the rules of the competition are almost identical in these two editions. In SDE14, special transports were prohibited on the competition site. An exception was made for small special transports. Special transports of category 1 according to the French road traffic regulations with the following dimensions were permitted: Width less than 3 m, length less than 20 m and weight less than 48 t (L'administration francaise, 2020). At the 2019 SDE in Szentendre (Hungary), all types of special transport were banned, no exceptions were made as in Versailles 2014. It is not clear from the rules whether there were

any agreements between the teams and the organisers. Due to the competition history and the time restrictions during the set-up, it is rather unlikely that all teams at the SDE 2019 managed without special transports.
The following Figure 4-6 shows an overview of the permissible transport dimensions according to the German Road Traffic Regulations. In order to keep transport costs as low as possible, the teams usually try to design in such a way that transport can take place without escort vehicles.



Breite (B) **Höhe (H)** **Länge (L)**	B 2,55 m H 2,90 m L 13,50 m	B 3,00 m H 2,90 m L 30,00 m	B 3,50 m H 2,90 m L 12,50 m	B 4,00 m H 3,10 m L 12,50 m	B 4,20 m H 4,20 m L 12,50 m	B 4,50 m H 4,20 m L 12,50 m	B 5,50 m H 4,20 m L 12,50 m
Genehmigung	keine	Ausnahmegenehmigungen erforderlich					
		meist sind Dauer-genehmigungen vorhanden	für die jeweiligen Transporte müssen separate Genehmigungen beschafft werden				
Begleit-fahrzeug			Begleitfahrzeug auf Bundesstraßen erforderlich				
			auf Autobahnen in AT immer, in DE/CH teilweise	Begleitfahrzeug auf Autobahnen erforderlich, in AT doppelte Begleitung			
Polizei-begleitung				Polizeibegleitung in DE/CH	immer mit Polizeibgleitung		
Sonstiges					Tiefladerkombinationen		

Figure 4-6: Maximum transport dimensions in Germany according to the German Road Traffic Regulations. Source: © Edition DETAIL (Huss et al., 2018, S. 58)

4.2.2 Time limitations for Assembly and Disassembly

As mentioned in the introduction, the challenge of the SDE is the temporary character of the event and the time frame. The timeline for assembly and disassembly, as well as for the Competition Days, is rather comparable to a trade fair. When comparing the European SDE competition with the US competition over a period of the past 13 years, two things stand out (Figure 4-7). Firstly, one sees that the time for assembly and disassembly is even more limited in the American competition than in the SDE. The duration of the assembly phase at Solar Decathlon (US) was on average 8 days, whereas the competition teams only had 3-5 days for de-assembly. In contrast, the range for the assembly of the SDE houses is from 10 to 15 days for assembly and 5 to 7 days for disassembly. Both assembly and disassembly times were higher for the first three editions of the SDE when considering the days available in comparison to the US competition of the same periods (SD2009, 2011, etc.). Since 2015, the assembly and disassembly times have converged between the SD and the SDE.
The second aspect is an increase in the number of working hours available for the construction phase, both for the SD and the SDE. At the US competitions, the site is open 24 hours a day for construction activities, so teams can run a three-shift operation to make the most of the time available. At the SDE, the opening hours have been limited to the period from 7:00 in the morning to 23:00 in the evening as for the 2019 competition in Szentendre. This means that night work is no longer permitted, so that the teams here have tended to operate their construction site in two shifts. This increases site safety for the students on site. After more working hours were available for assembly and disassembly at the beginning of the SDE, the working hours have been brought back into line with the US competition since the SDE 2019. Although the working hours per day were limited to 16 hours per day at the SDE, the number of assembly and disassembly days was increased in return.

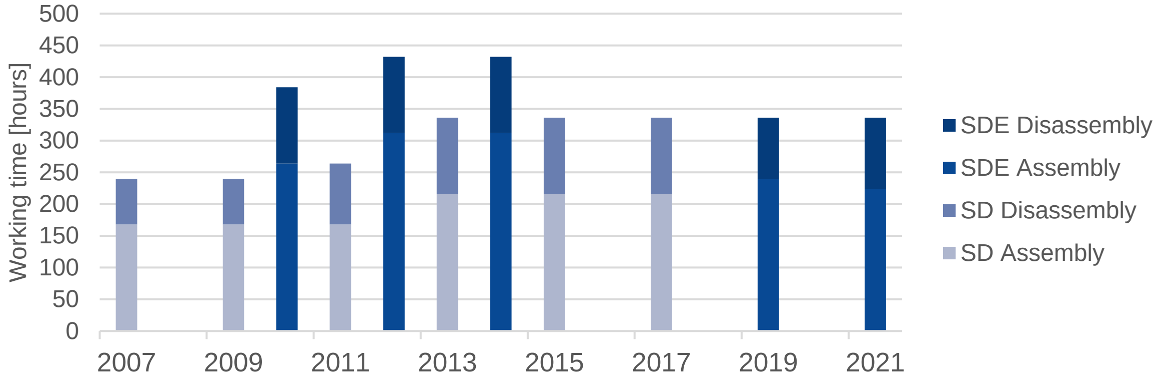


Figure 4-7: Comparison of total labour hours for assembly and disassembly between the Solar Decathlon competitions in the USA (SD) and the Solar Decathlon Europe editions (SDE). Source: Frauke Rottschy, University of Wuppertal

4.2.3 Results

In the overall picture, it is surprising that a significant proportion of the teams work with elements (wall, ceiling) instead of room modules (e.g. SDE 2010: elements 41%, modules 59%, Figure 4-8). As a tendency can be discerned, that teams are increasingly working with elements. The use of room modules has decreased over the past four SDE competitions. There are even a few examples where only the primary structure/shell was prefabricated and delivered in larger elements or modules. As a consequence, a lot of work has to be done in a very limited time at the venue, which is to the detriment of the students (stress) and the quality (execution under high time pressure and with limited means (e.g. tools, materials, etc.).
By evaluating the projects according to the system described above, one can see that the majority of the most successful teams in the competition have a high or very high level of prefabrication. At the SDE 2010 in Madrid, for example, the teams in 1st to 5th place overall all worked with space modules. An extreme case has been the competition winning team from Virginia Tech with their Lumen House. The team delivered a completely operational and ready-to-use building in one piece. With 95% prefabrication, the team leads the list of all 65 houses by far. Second in the ranking for highest degree of prefabrication is Team Grenoble's Armadillo Box at SDE 2010 with 85%. The Grenoble team placed fourth in the competition at that time. The team with the lowest score of only 20% and thus a very low level of prefabrication is the project "Sunflower" by the Chinese team from Tianjin. The team had brought only OSB panel-covered wall elements to the competition site and carried out all other work on site.

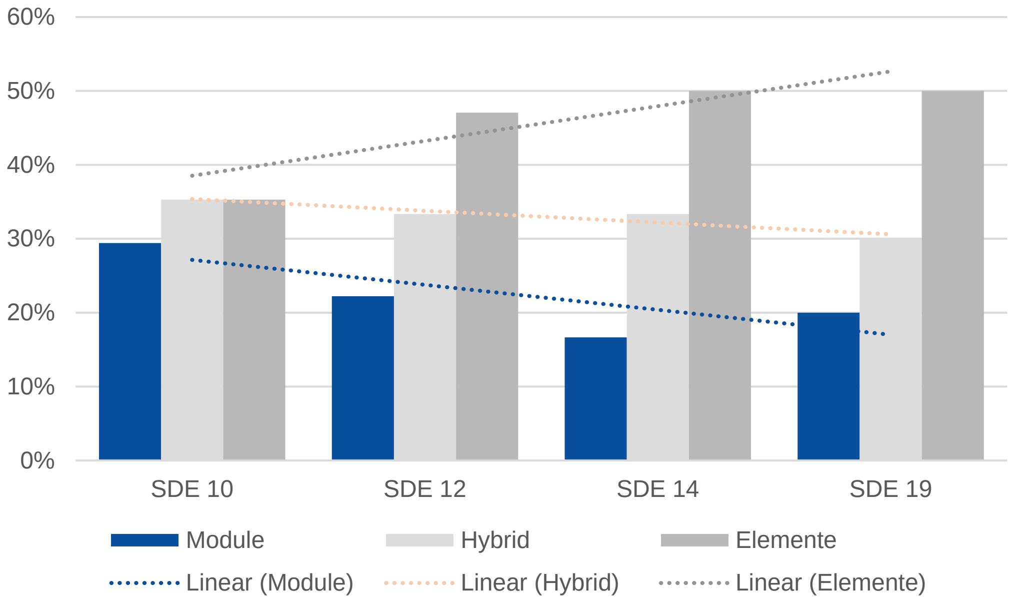


Figure 4-8: Development of the share (in %) of modular, hybrid and element-based buildings in the SDE competitions in the years between 2010 and 2019. Source: Frauke Rottschy, University of Wuppertal.

In Table 4-4 the analysed projects and the points given are shown in detail. The projects are listed chronologically according to the SDE-Editions in which they participated, starting with the SDE 2010. They are listed from first place in the overall ranking to the last place. The overall result concerning prefabrication is shown in the last column in percent.

Table 4-5: Overview on the points given in each category for all SDE houses

Project Name & City	Overall Award (Ranking)	Type of Prefabrication	Connections	No. of Modules/ Elements	Technical Core	Façade	Roof PV	Detailing of Joints	Technical Installation	Transport	Degree of Prefabrication (%)
SDE 2010											
LumenHAUS_Blacksburg	1	●●●	●●●●●	●●●●●●	●	●	●	●	●	●	100%
IKAROS Bavaria_Rosenheim	2	●●●	●●●●●	●●●●●	○	○	○	●	●	●	80%
home+_Stuttgart	3	●●	●●●	●●●●●	○	○	○	○	○	●	55%
Armadillo Box_Grenoble	4	●●	●●●●●	●●●●●	●	○	○	●	●	●	80%
Luuku House_Helsinki	5	●●	●●●	●●●●●●	○	○	○	○	●	●	65%
Wuppertal house_Wuppertal	6	●	●●●	●●●	●	○	○	○	○	●	45%
Napevomo_Paris	7	●●●	●●●	●●●●●	○	●	○	○	○	●	65%
RE:FOCUS_Gainesville	8	●●	●●●	●●●●●●	○	●	○	●	●	●	75%
SMLhouse_Valencia	9	●●●	●●	●●●●	○	○	○	○	○	●	50%
Living Equia_Berlin	10	●	●●●	●	○	○	○	○	○	○	25%
Bamboo House_Shanghai	11	●	●●●●	○	○	○	○	○	○	○	25%
Solarkit_Sevilla	12	●	●●●	●	○	●	○	●	○	●	40%
Low3_Barcelona	13	●●	●●●●	●●●●●	○	●	○	●	●	●	75%
Urcomante_Valladolid	14	●●	●●●	●●●●	○	○	○	○	○	●	50%
H.O.U.S.E_Nottingham	15	●●●	●●●●	●●●●	○	●	○	●	●	●	75%
Sunflower_Tianjin	16	●	●●●	○	○	○	○	○	○	○	20%
Fab Lab_Barcelona	17	●	●●●	●●●	○	●	●	●	○	●	55%
SDE 2012											
Canopea_Grenoble	1	●●●	●●●	●●●	●	●	●	●	●	○	70%
Patio 2.12_Sevilla	2	●●	●●●	●●●●●	●	○	●	●	●	●	75%
Med in Italy_Rome	3	●	●●●	●	○	○	○	●	○	○	30%
Ecolar_Konstanz	4	●	●●●●●	●●	○	○	○	○	○	○	40%
CounterEntropy_Aachen	5	●●	●●●●●	●●●●	●	○	○	○	●	○	65%
Odoo Project_Budapest	6	●●●	●●●●	●●●●	○	○	○	○	○	●	60%
SML system_Valencia	7	●●●	●●●	●●●●●	●	●	○	●	●	●	80%
(e)co _Barcelona	8	●●	●●●	●●●●●	○	●	○	●	○	○	60%
Prispa_Bucharest	9	●●	●●●	●●●●●●	○	●	○	○	○	○	60%
FOLD_Copenhagen	10	●	●●●	●●	●	○	○	●	●	○	45%
ParaECOHouse_Tongji	11	●	●●●	○	●	○	○	●	●	○	35%
Ekihouse_Victoria-Gasteiz	12	●●●	●	●●●●	●	●	○	○	●	●	60%
SUMBIOSI_Bordeaux	13	●●	●●●	●●●●●	●	○	○	○	○	○	55%
ekohouse_Sâo Paulo	14	●	●●●●●	●●	○	○	○	○	○	○	40%
Omoenashi House_Chiba	15	●	●●●	○	○	○	○	●	○	○	25%
Cem+nem-_Porto	16	●●	●●●	●●●●	●	○	○	●	○	●	60%
House Pi Unizar_Zaragoza	17	●	●●●	○	●	●	○	○	○	○	30%
estonyshine_Paris	18	●	●●	●●●	○	○	○	●	○	●	40%
SDE 2014											
RhOME for DenCity_Rome	1	●	●●●	○	●	○	○	○	○	○	25%
Prêt-à-Loger _Delft	2	●	●●●	○	○	●	○	○	○	○	25%
Roof Top _Berlin	3	●	●●●	○	●	○	○	●	○	●	35%
you+ _Lucerne	4	●●	●●●	●●●●	○	●	○	○	○	●	55%
Casa Fenix_La Rochelle	5	●●●	●●●	●●●●●	○	●	●	○	○	●	70%
Embrace_Copenhagen	6	●●	●●●	●●●●●	○	○	●	○	○	●	60%
Maison Reciprocity_Ángers	7	●●●	●●●	●●●●	●	●	○	○	○	○	60%
Resso _Barcelona	8	●	●●●●●	○	○	●	○	○	○	○	35%
Renai House _Chiba	9	●●	●●●	●●●●	●	○	○	○	●	○	55%
Orchid House_Taipei	10	●	●●●	○	○	○	○	○	○	○	20%
On Top _Frankfurt	11	●	●●●	●●	●	●	○	○	○	●	45%
CASA _Mexico City	12	●	●●●	○	○	○	○	○	○	○	20%
Techstyle Haus_Providence	13	●●	●●●	○	●	○	●	○	○	○	35%
Symbcity house_Ciudad Real	14	●	●●●	●●	●	○	○	○	○	○	35%
Tropika_San José	15	●	●●●	○	●	○	○	○	○	○	25%
Baan chan_Bangkok	16	●●●	●●●●	●●●●	○	●	○	●	○	●	70%
H°_Mumbai	17					-no data available -					
EFdeN _Bucharest	18	●●	●●●	○	○	○	○	○	○	○	25%
Liv-Lib'_Paris	19	●●	●	●●●●●	○	○	○	○	○	●	45%
PHILÉAS_Nantes	20					-no data available -					

Table 4-4 (cntd.): Overview on the points given in each category for all SDE houses

Project Name & City	Overall Award (Ranking)	Type of Prefabrication	Connections	No. of Modules/ Elements	Technical Core	Façade	Roof PV	Detailing of Joints	Technical Installation	Transport	Degree of Prefabrication (%)
SDE 2019											
Habiter2030_Lille	1	●●●	●●●	●●●●	●	○	○	○	○	●	60%
MOR_Delft	2	○	●●●	○	●	○	○	○	○	○	20%
Over4_Bucharest	3	●●	●●●	●●●●●●	●	○	○	○	○	●	65%
The mobble_Ghent	4	●●	●●●	○	○	●	○	○	○	●	35%
SOMESHINE_Miskolc	5	●	●●●	○	○	●	○	○	○	○	25%
Azalea_València	6	●	●●●	●●	●	○	○	○	○	●	40%
resilient nest_Bangkok	7	●	●●●	○	○	○	○	○	○	○	20%
TO_Barcelona	8	●	●●●	○	○	○	○	○	○	○	20%
koeb_Budapest	9	●●	●●●	●●●●●●	○	●	○	●	○	●	70%
AURA_Sevilla	10	●●●	●●●	●●●●	○	●	○	●	○	○	60%

Legend: ○ = 0 Points; ● = 1 Point; ●● = 2 Points; ●●● = 3 Points; … ; ●●●●●● = 6 Points

Figure 4-9 shows the correlation between the degree and type of prefabrication of the SDE houses and the result of the respective teams in the competition. The x-axis shows the position of the teams in the overall ranking. The y-axis shows the degree of prefabrication (in %). Mentioned by name in the graph are the buildings described in the appendix. Marked with a diamond are the buildings that were built entirely or partially as room modules.

In addition to the SDE houses from the competitions between 2010 and 2019, two comparative projects from the Solar Decathlon US 2007 and 2009 were also shown. These are the two award winning houses in the overall ranking from the TU Darmstadt team. Both houses can compete with Virginia Tech's Lumen House with prefabrication rates of 90% and 95%. The first three places of the SDE 2010 competition were all in the top half of the prefabrication ranking. All the teams in 1st to 3rd place built their houses with room modules. In subsequent editions, this correlation is no longer quite as clear as in the SDE 2010, but a tendency towards higher levels of prefabrication in the top places and lower levels of prefabrication in the lower-placed houses can be seen in all competitions between 2010 and 2014. In the 2019 competition, very low levels of prefabrication were observed for the houses overall.

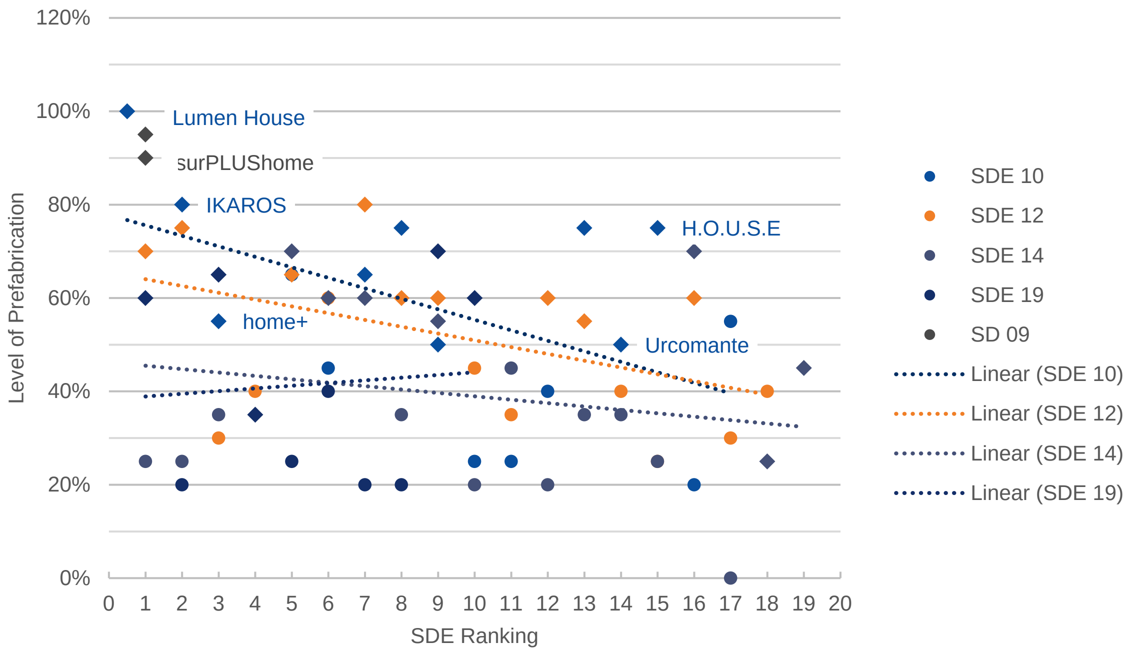


Figure 4-9: Correlation of the level and type of prefabrication (in %) and the result of the respective teams in the competition. The top positions tend to have higher degrees of prefabrication. Source: Frauke Rottschy, University of Wuppertal

The characteristic features of the houses (see chapter 4.4 -Project examples) are also reflected in the evaluation matrix. Table 4-5 shows the characteristics of the house with the highest (Lumen House) and lowest rating (Sunflower). To show the whole range of prefabrication levels, a project with a medium rating is also listed (Urcomante). The detected correlation between level of prefabrication and success in SDE Competitions leads to the conclusion that it is worthwhile for the teams to invest a lot of time and energy in planning and serial production. In the successful projects, one can see a high quality in the engineering work, but also a close coordination with the consulting specialists from timber construction companies or the building industry. With the extremely tight schedule on site, this approach seems inevitable. In terms of construction logistics and execution, the Solar Decathlon is certainly the Formula 1 of the construction industry. Comparable to the pit stop of a racing car, at the SDE one can see immediately, which strategy is successful, and which is not. Many teams have also been continuously taking part in Solar Decathlon competitions for years and some of them have gradually optimized their design strategies. The degree of professionalism is increasing, and the knowledge and network of partners involved is growing.

Table 4-6: Comparison of the individual criteria of three houses

Category	Lumen House	Urcomante	Sunflower
Type of Prefabrication	Modules	Modules	Elements
Connections	Plugged	Screwed	Screwed
Number of Modules/ Elements	1-2	5-10	> 40
Technical Core	Core Element	No Core	No Core
Façade	Pre-mounted	Non-pre-mounted	Non-pre-mounted
Roof-PV	Pre-mounted	Non-pre-mounted	Non-pre-mounted
Visibility of joints	No fittings	No fittings	No fittings
Technical Installations	Plug & Play	Installation on-site	Installation on-site
Transport	Special	Special	Standard
Level of Prefabrication	Very high	Medium	Very low
in %	100%	55%	20%

Figure 4-10 illustrates once again the relationship between the construction method and the degree of prefabrication achieved by the SDE houses in 2010. The houses are arranged from left to right and from a low to a high degree of prefabrication. The category of prefabrication is considered on the y-axis. The graph illustrates the relationship between buildings constructed from space modules and an associated high degree of prefabrication (buildings on the right). The buildings constructed from flat elements tend to be in the middle or lower range when looking at the degree of prefabrication.

Figure 4-10: Comparison of the different prefabrication levels of SDE houses in 2010, ascending from low level (left) to high level (right). Source: Frauke Rottschy, University of Wuppertal

The two winning entries from the TU Darmstadt at the Solar Decathlon 2007 and 2009 in Washington were examined and compared with the houses from the SDE. It is striking that both houses from the TU Darmstadt have a very high degree of prefabrication. The houses were optimised for transport from Germany to Washington D.C. in the design process. Great attention was paid to assembling as many components as possible in advance in order to minimise the effort on site. The risk of possible transport damage, e.g. the risk of glass breakage to the large-format over-corner glazing or the glass thin-film modules on the façade of the surPLUShome, was evaluated during the planning process. Comparing these risks against the risk of a house not being completed at the competition in Washington, the two teams accepted them. With values of 90% and 95% for the degree of prefabrication, the houses of the TU Darmstadt, together with the Lumen House of Virginia Tech, occupy the first three places of all Solar Decathlon houses examined. All three houses took first place in the overall competition in different editions of the Solar Decathlon and were able to convince with their design strategies.

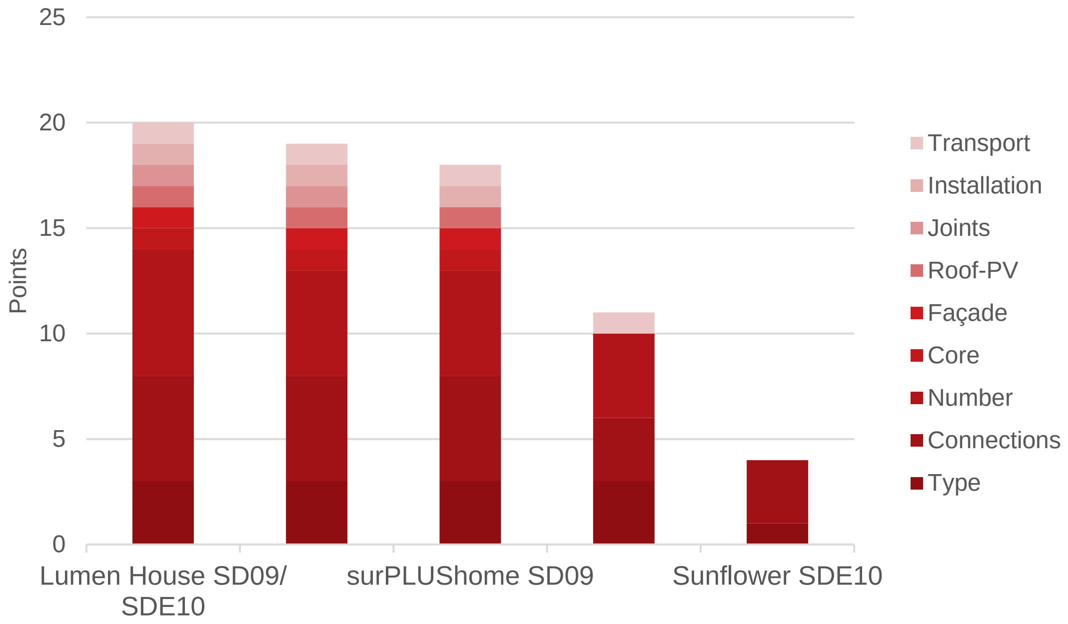


Figure 4-11: Comparison of the individual ratings of five Solar Decathlon houses. Source: Frauke Rottschy, University of Wuppertal

4.3 Conclusion and Outlook

When looking at the technically advanced production of timber construction modules by the leading timber construction companies (in conjunction with planners specialising in timber construction), one quickly realises that the students' buildings are less professionally built. This is mainly due to the competition's motto ‘Design, Built, Operate’, which motivates the participants to lend a hand themselves and thus gain valuable experience in both holistic planning and concrete implementation on a 1:1 object. But compared to conventional buildings, which are mainly erected on site, the SDE buildings, with their sophisticated technology and design, perform well overall in terms of their engineering performance and high levels of prefabrication. Very high and high degree of pre-assembly (façade, windows, PV, interior fittings and technology core (plug & play) is achieved in approx. 35% of the houses.

Experimental prototypes are created at the SDE, which are optimised for transport and speed of assembly and disassembly, but usually disregard economically scalable solutions. The SDE houses can demonstrate the advantages of prefabricated buildings, as this is inherent in the competition format and can very well leave a learning experience through the ways in which the buildings are presented to a broad public in mostly prominent locations.

System optimisation regarding the repetition of the same elements and components or measures for saving construction materials (e.g. in the case of necessary doubling of the primary construction in two-storey

room models) can be observed to a lesser extent overall. Some of the teams formulate economic concepts for scaling, but the focus is on the implementation of the prototype. It is remarkable in this context that for most of the participants in the competition it is the first self-built house.
The cross-sectional analysis of the SDE houses established since 2010 yields interesting findings in several respects. On the one hand, the evaluation of the houses shows that there are considerable differences in the strategies of the teams. Teams such as Virginia Tech or the team from Grenoble can convince with a very well-thought-out concept of prefabrication, which gives them advantages in assembly and disassembly and during the competition itself. A correlation between the engineering performance, especially in terms of elementation or modularisation, and the transportability of the houses was found. Another finding from the comparative analysis of the houses is that many the teams have only partly taken advantage from potential offered by modern production methods and construction techniques.

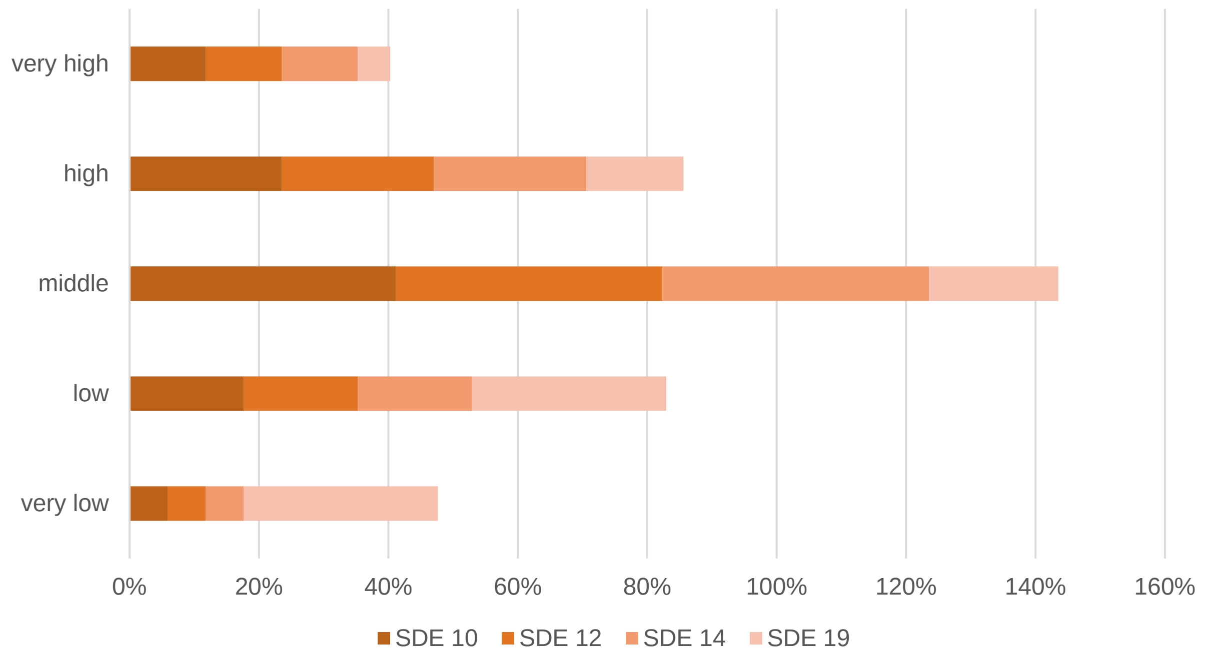


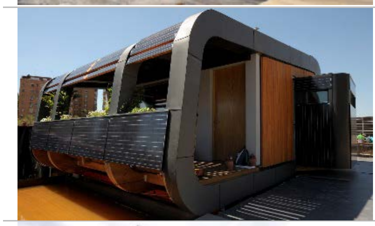
Figure 4-12: Percentage distribution of the level of prefabrication from very low to very high in five gradations. The largest proportion is in the range of the medium degree of prefabrication. Source: Frauke Rottschy, University of Wuppertal

The presentation of the modules and joints in the drawings (there are no 1:20 detail sections through the buildings) should be more focused on in the future. It is noticeable that the modules or elements are insufficiently labelled and dimensioned. There is also no colour marking of the modules and elements in the drawings. There is great potential in establishing as competition requirement a 3D or BIM model that represents clearly the modularity of the SDE houses. In the previous competitions, no CAD data was archived, resulting in a high loss of knowledge and data of the buildings after the end of the project. By storing vector-based data, it is also possible to subsequently retrace how the buildings were designed and constructed. Both the construction and the technical building equipment can thus be better understood. At SDE21/22, teams will submit complete BIM models for the first time.
For the Solar Decathlon 2021/22, the focus will be exclusively on multi-storey construction methods in existing buildings. This shift within the Solar Decathlon leads to a better transferability to current building tasks, especially in the area of residential construction. The first approaches to dealing with existing buildings (additions, conversions, extensions) were already presented at the Solar Decathlon Europe 2014 in Versailles. There, concepts for the implementation of entire residential quarters were also considered. However, the connection to the existing buildings was only solved schematically. The transition between new and old, the handling of statics (use of load reserves, introduction of a load distribution level) and construction logistics within densely built-up urban quarters offer exciting tasks and are being intensified in the current SDE21/22 competition.

4.4 Project Examples

In the following chapter, five projects from the SDE 2010 in Madrid are described in detail and compared with each other. The projects are introduced with a short textual description and presented with selected photos from the event and the construction phase. In addition, some relevant detailed drawings are provided, from which the main features of the respective building become clear. During the selection process, special attention was paid to showing particularly exciting aspects or innovative technical solutions. The broad field of projects presented here cover three different perspectives. The ranking in the overall competition, the degree of prefabrication evaluated in the analysis and interesting individual criteria and technical solutions of the respective design. The five sample projects are listed in the overview table.

Table 4-7: Overview of the five sample projects. Source: (SDE flickr, 2010)

Project		**Level of Pre-fabrication**
	**IKAROS Bavaria** University of Applied Sciences Rosenheim Germany	**80%** High
	**Nottingham H.O.U.S.E** University of Nottingham United Kingdom	**75%** High
	**home +** University of Applied Sciences Stuttgart Germany	**55%** Medium
	**Urcomante** Universidad Vallalodid Spain	**50%** Medium
	**Lumen House** Virginia Polytechnic Institute and State University USA	**100%** Very High

4.4.1 A1 – IKAROS Bavaria

Figure 4-13: Exterior view of IKAROS Bavaria at Villa Solar in Madrid. Source: Solar Decathlon Europe (SDE flickr, 2010)

The Rosenheim University of Applied Sciences building consists of four room modules. Module joints specially developed for the project were used to connect the modules. The system is reversible and easy to assemble. The team describes their strategy as follows: ‘The architectural requirements suggest a frame construction as the ideal construction approach. Because wood is indisputably the most sustainable of all available construction materials, it was clear to us that this is the only material we want to use for the main structure. […]’. The IKAROS Bavaria House achieves 16 out of 20 possible points in the evaluation matrix. With 80%, it achieves a high degree of prefabrication, and the house's overall rating is on the threshold of the highest rating level.

A special feature of the project resides in standardised module connectors that are inserted into each other and are therefore reversible, as can be read in the team's description of the system: *‘After exact alignment, the modules are simply hooked into each other. The forces at the edges of the modules are transmitted via the Walco V80 connectors. This allows the horizontal forces to be transferred via the base and top plates into the wall plates and finally via the foundation into the ground. [...] Since all built-in furniture and sanitary fittings are already integrated into the modules, the heaviest module weighs 7.2 tonnes, despite the use of lightweight materials.’*

Figure 4-14: Detail of the Walco V80 module connector and test assembly of the first module by Team Rosenheim. Source: Technische Hochschule Rosenheim, Engineering & Construction Report, page 5 (Knowledge Platform)

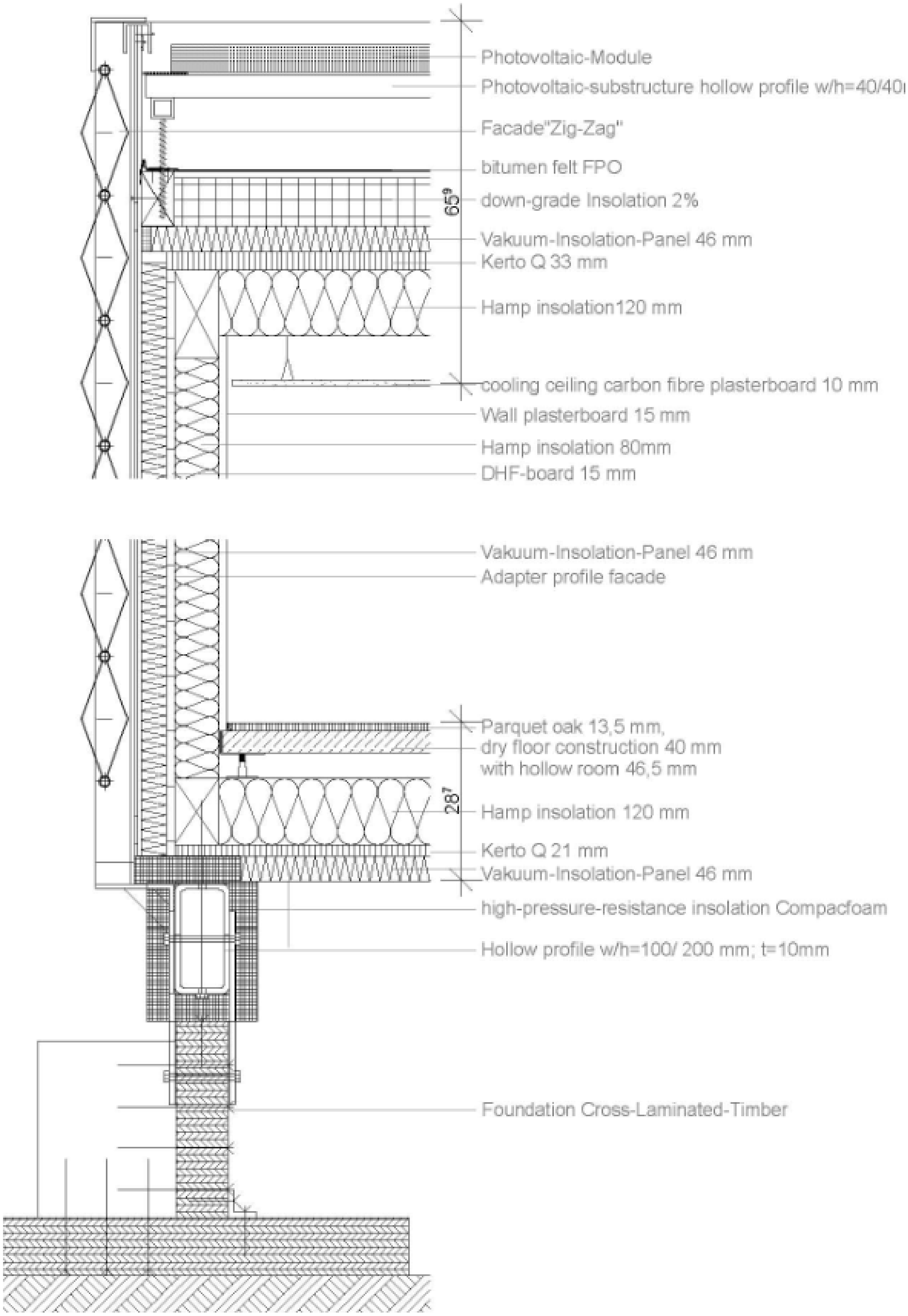


Figure 4-15: Façade section of the modular building by the IKAROS Bavaria team. Source: Rosenheim University of Applied Sciences, Engineering & Construction Report, page 7 (Knowledge Platform)

4.4.2 A2 – Nottingham H.O.U.S.E

Figure 4-16: Exterior view of the Nottingham H.O.U.S.E at SDE 2010. The team chose to leave the joints between the elements visible and cover them with reversibly fixed moulded metal parts. Source: Solar Decathlon Europe (SDE flickr, 2010)

The experimental Solar Decathlon Europe houses are optimised for multiple assembly and disassembly. Therefore, the architecture students make sure that all constructive connections are reversible (e.g. joint visible inside and outside). At the Nottingham H.O.U.S.E. you can see how the joint is handled very well. The team around Prof. Mark Gillott from the University of Nottingham (University of Nottingham, 2020) made the decision to leave the joint between the room modules visible in the façade. The overlapping of the joint between the modules is solved by a C-profile made of aluminium. Inside the building, after assembly, MDF panels are attached to the joints, which are fixed with screws and thus can easily be removed again.

The Nottingham team describes the construction and design process decisions in their Construction Report in the Project Manual as follows: *'**Very early on in the design stage we decided on the method of prefabrication** and where possible the modular and structural approach have been expressed as part of the internal strategy. This early decision meant that the method of construction and the architectural expression are inextricably linked. A **modular panel design** meant that the **house is essentially split into eight parts**, and so these joints can be seen throughout the house, expressing the method of construction which provides a sustainable story about **efficient prefabrication**.'*

In SDE buildings with a high degree of prefabrication, as many components as possible are preassembled. In addition to the windows and the façade, the roof insulation with sealing and the roof photovoltaic system are often preassembled as well. In some houses, the interior fittings and furniture are also installed and delivered in advance, so that the houses are essentially ready for use. Only the technical connections (water, sewage and electricity), as well as the outdoor facilities on the plot, are constructed on site.
The Nottingham H.O.U.S.E achieved 15 out of 20 points with their building of eight room cells and showed a high degree of prefabrication (75%). The windows and façade of the building were already preassembled and the module joints only had to be connected inside and outside with prefabricated fittings. The building

services were also completely pre-installed, making this building an easily tradable modular construction. Only the roof PV system had to be installed on site at the competition site. The photo shows the still open joints between the lower modules and the temporary state of construction on the upper floor. The detailed drawing shows the module joint with cladding made of an aluminium C-profile.

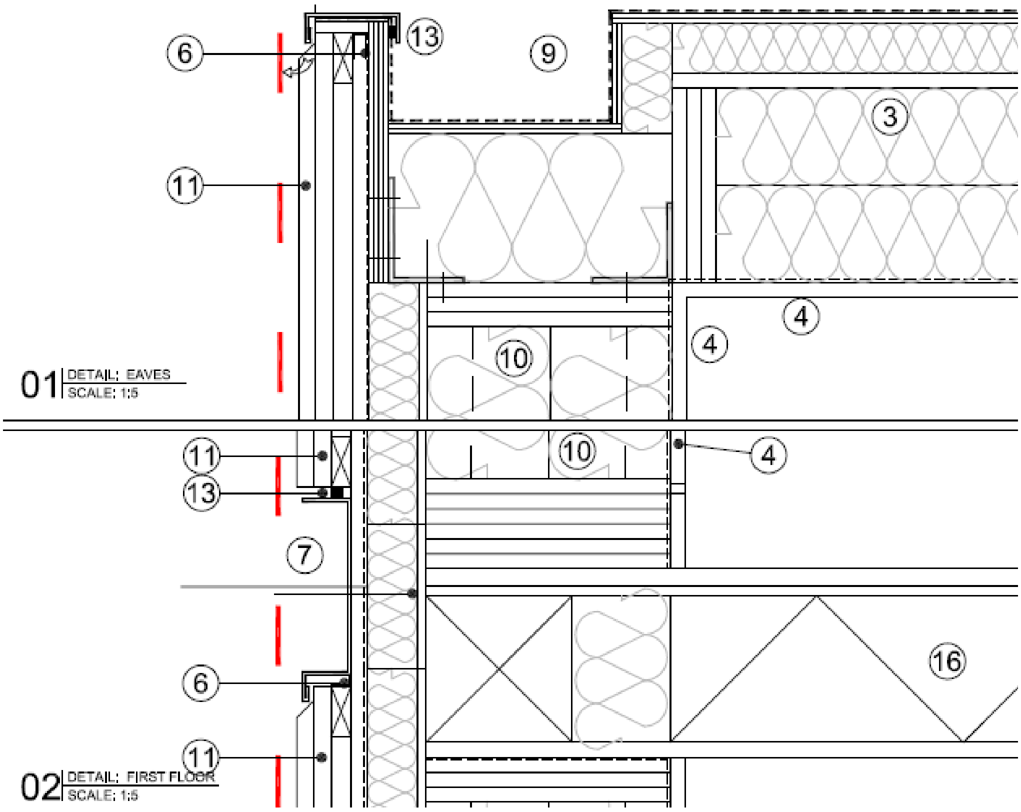


Figure 4-17: Vertical section through the façade of the Nottingham H.O.U.S.E with visible module joint between lower and upper module. The joint is covered by PPC aluminium cover plates, which are applied after the modules have been installed (see no. 7 in the drawing). Source: University of Nottingham, Construction Drawings, page 62 (Knowledge Platform)

Figure 4-18: The Nottingham H.O.U.S.E being assembled. The four lower modules have already been assembled, the first upper module is currently being placed by crane. Source: Solar Decathlon Europe (SDE flickr, 2010)

4.4.3 A3 – home +

Figure 4-19: Exterior view of the home+ contribution of the Stuttgart University of Applied Sciences at the SDE 2010 in Madrid. Source: Solar Decathlon Europe (SDE flickr, 2010)

It is also interesting to compare the level of detail during the planning planning using 3D or BIM models with the actual execution. In the case of the home+ at the Stuttgart University of Applied Sciences, the 3D model was modelled with all the details that are important for the execution. For example, on the water-bearing layer of the façade, the pre-mounted fastening points of the photovoltaic modules, which are installed on site on the four room modules, can be seen.

*'The key design characteristic of home+ is the rhythmic arrangement of **building modules and gaps**. The building volume mainly consists of **four modules**, three with the same dimensions and an additional smaller loggia module. The modules have no wall openings in the east and west, the gaps have the function of climate gaps to ventilate and expose the interior. This arrangement results not only from the separation of the floor areas and functions but also follows aspects of modularity, installation and transport.'*
The home+ achieves 12 out of 20 points with the type of construction and thus has a medium degree of prefabrication (60%). The team utilised prefabricated room modules, where the windows, for *example*, were already preassembled. However, the connecting glass elements between the modules and the photovoltaic façade had to be installed on site. The same applies to the roof photovoltaic system.

In the case of the home+, the main components of the building were prefabricated. The rhythmically repeating glass sections of the building and the outer level of the façade were assembled on site, which is why the house as a whole only has an average degree of prefabrication of 60%. In any case, the team can be credited with a high level of engineering performance in the run-up to the competition, as the house was 3D designed down to the last detail in advance. This made it possible to precisely determine the assembly costs in advance. The functions from the CAD system available in 2010 were fully used for the planning of home+. Since the house was built in 2010, it cannot be assumed that the 3D model already contains BIM elements.

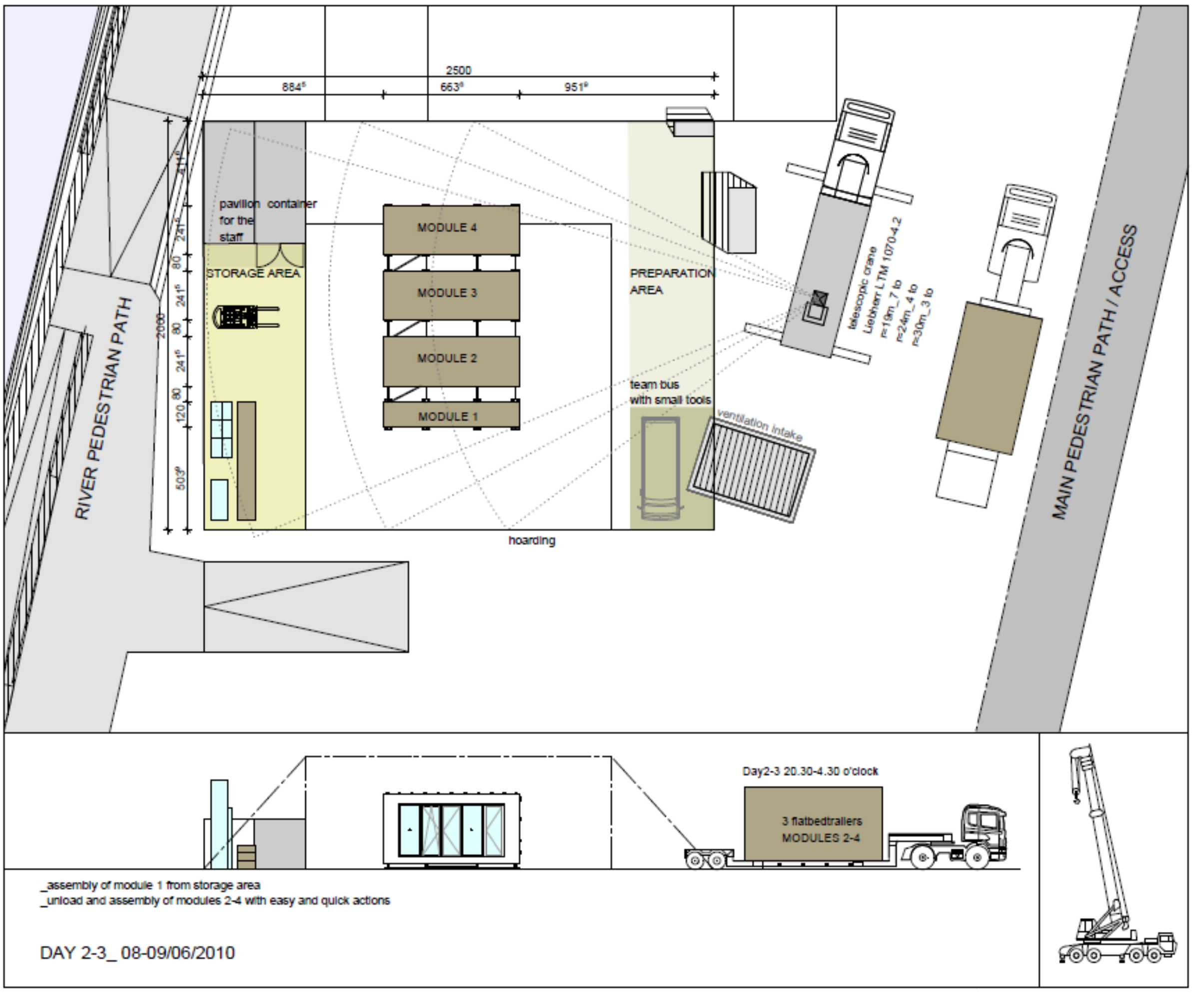


Figure 4-20: Overview of construction site logistics at the home+ on Villa Solar in Madrid. Source: University of Applied Sciences Stuttgart, Construction Drawings, page 250 (Knowledge Platform)

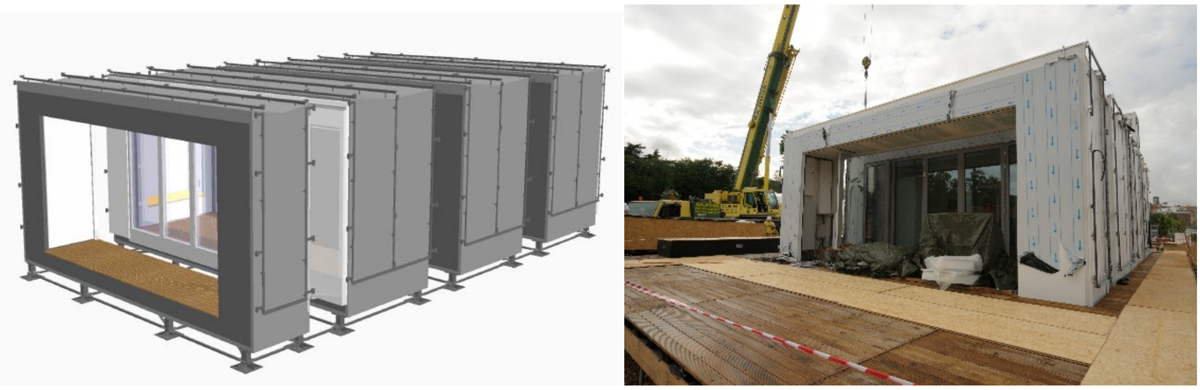


Figure 4-21: Comparison of the 3D planning of the modules of the home+ of the HFT Stuttgart with the state of construction during the construction phase on the competition site in Madrid. Source: University of Applied Sciences Stuttgart, Construction Drawings, page 268 und Solar Decathlon Europe (SDE flickr, 2010)

4.4.4 A4 – Urcomante

Figure 4-22: The house entitled Urcomante by the University in Vallalodid with façade-integrated PV and water basin in the foreground. Source: Solar Decathlon Europe (SDE flickr, 2010)

In the planning phase, the teams spend a lot of time making detailed decisions about the degree of prefabrication and also about the concrete construction process. By means of a site operation plan, the delivery and assembly of the modules and components is pre-planned step by step and recorded in a meticulous schedule (example Urcomante). The team at the university in Vallalodid in northern Spain planned all the assembly steps of their house in advance using three-dimensional axonometries. The "Urcomante" house was divided into a total of six parts for transport. Only the relatively low degree of prefabrication of the three roof-wall and three floor-wall modules is surprising given the high precision in the planning of transport and assembly. The SDE House Urcomante has a medium degree of prefabrication (55%) - and is thus in the midfield.

‘The constructive *solutions adopted are* ***dry construction and simple to execute****. Most of the materials used are* ***wood or wood composition*** *in the shell, while the space is closed with glass in its south, east and west facades. The materialisation of the shell […] becomes one of the most relevant aspects of the project, as it will be the one that achieves the correct integration of all the systems. The enclosure of the functional modules also assumes capture properties, which are integrated in an alternation of opaque glass and photovoltaic panels, as in the enclosure.’*

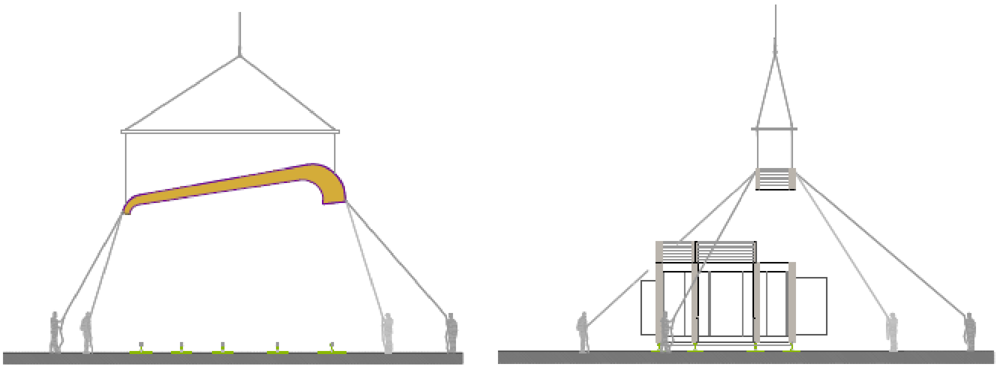


Figure 4-23: Illustration of the state of construction with a roof module during assembly. Source: Universidad Valladolid, Construction Drawings, Page 205 (Knowledge Platform)

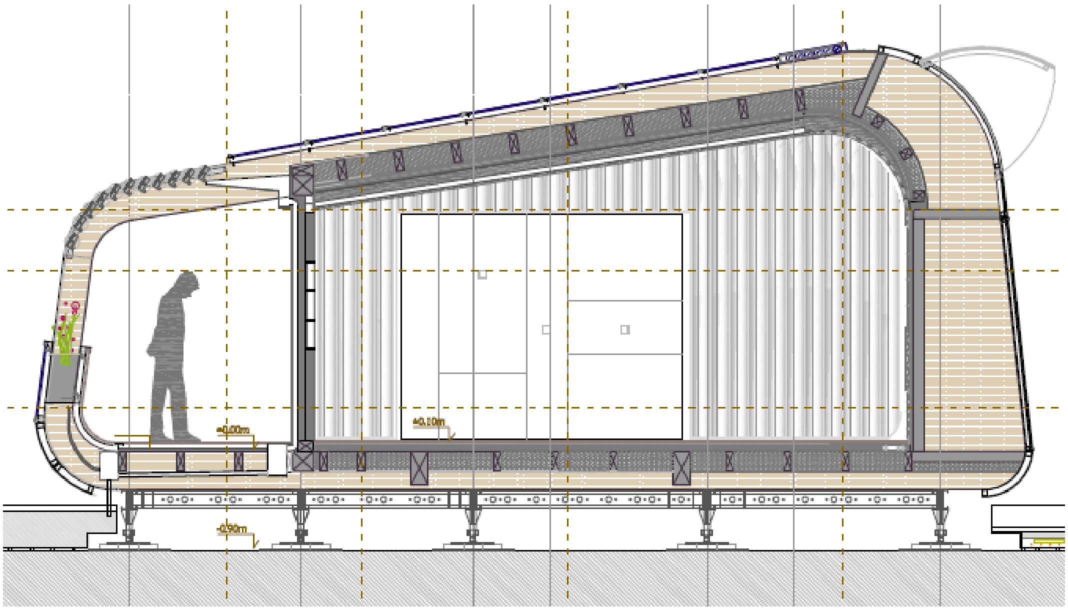


Figure 4-24: Longitudinal section through the SDE Urcomante house with visible joint. Source: Universidad Valladolid, Construction Drawings, page 34 (Knowledge Platform)

Figure 4-25: Interior view of the building during on-site construction. You can see that essentially only the wooden elements were delivered in the shell state. Source: Universidad Valladolid, Construction Drawings, page 9

4.4.5 A5 – Lumen-House

Figure 4-26: Exterior view of Virginia Tech's Lumen House at SDE2010 in Madrid. The house was perfectly designed for transport conditions and can be transported in one piece with all façade and roof cladding. Source: Solar Decathlon Europe (SDE flickr, 2010)

Comparing the previous houses with the house with the highest ranking in the analysis, the differences in design performance and execution become obvious. The Virginia Tech team designed and built a most optimised module with their Lumen House at SDE 2010. Virginia Tech's Lumen House was optimised to meet the requirements of the competition. The house is designed as a single module to reduce the construction time to a minimum. It houses all the functions for the residents and includes a central technical room on the east façade of the house. With this approach, the Lumen House achieves a very high degree of prefabrication of 100% with 20 out of 20 possible points.
The situation at the competition was as follows: A heavy duty vehicle drives up to the Villa Solar at the Solar Decathlon Europe in Madrid. Fully wrapped in white transport foil, the Lumen House arrives at the competition site. The building is 10.20 m long, 3.20 m wide and 3.00 m high, making it one of the larger modules in the cross-comparison of the four SDE competitions considered. The Lumen House was very clearly designed and optimised to meet the competition regulations. It is very similar in its approach to the Tiny Houses currently trending. Transportable in one piece, fully equipped, plug & play or even self-sufficient.

Figure 4-27: Illustration of the drop deck loader that can transport the module with a length of 10.20 metres. Source: Virginia Polytechnic Institute and State University, Construction Drawings, page 132 (Knowledge Platform)

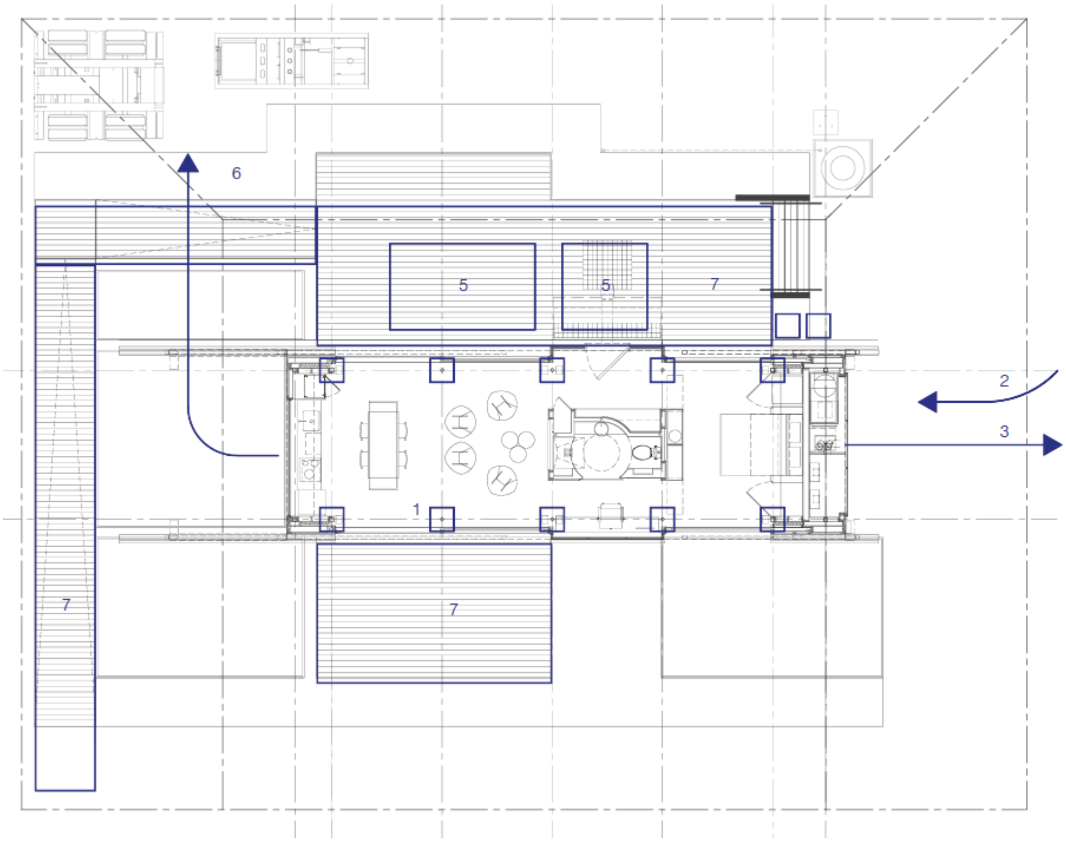


Figure 4-28: The Site Operations Plan shows the construction of the Lumen House. The module rests on ten-point foundations and is lowered in one piece by a crane. Source: Virginia Polytechnic Institute and State University, Construction Drawings, page 129 (Knowledge Platform)

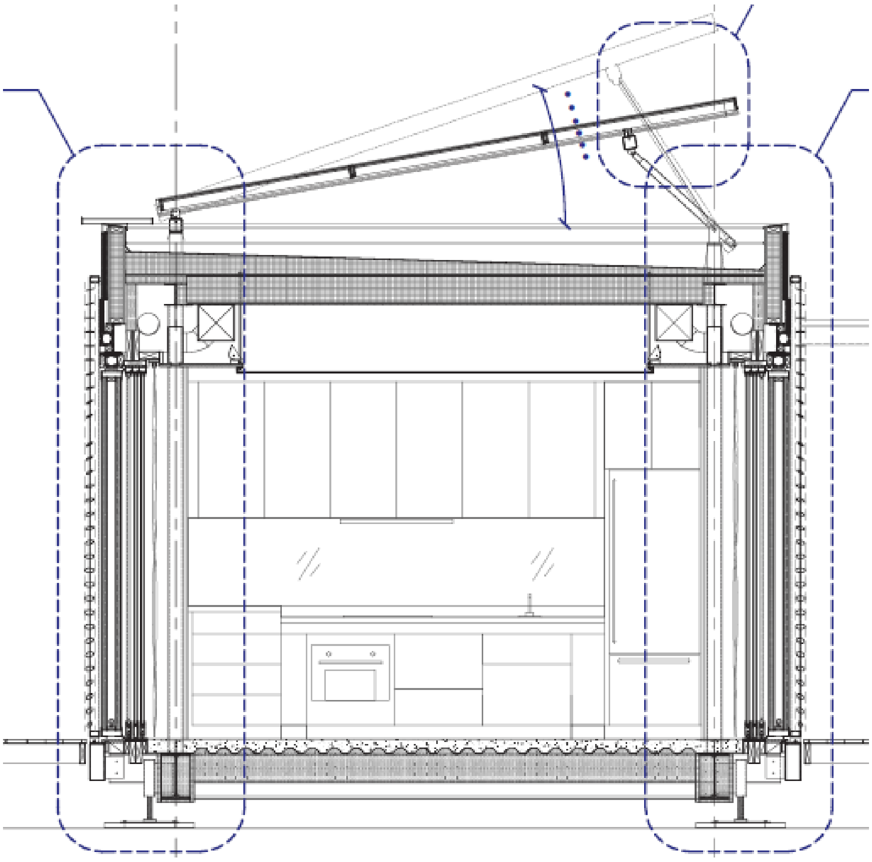


Figure 4-29: Cross-section through the building showing the roof-mounted PV system that can be set up using a telescopic arm. Source: Virginia Polytechnic Institute and State University, Construction Drawings, page 21 (Knowledge Platform)

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5. Sustainable and Recyclable Construction in Solar Decathlon Europe

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5.1 Introduction

The building sector has been faced with the issue of sustainability for many years now. While the energy consumption per area in the use phase of buildings has steadily decreased due to stricter specifications, a sustainable use of resources has hardly been established in the building industry so far. The deconstruction of buildings, let alone the possibility of using recycled building materials in the sense of circular construction and so-called "urban mining", is usually not yet considered in planning.
Sustainable construction can be achieved through the following three strategies, which are ideally pursued in combination:

- **Efficiency:** Through better quality, less energy is consumed for a service. This applies to the thermal insulation of buildings as well as to building services engineering. An efficient heat generator provides more useful heating from less final energy.
- **Sufficiency:** Sufficiency pursues the approach of savings by producing and consuming less. Less living space per person, for example, results in lower energy and material requirements per person, so that resources are saved. This can counteract rebound effects.
- **Consistency:** The consistency approach pursues the goal of environmental compatibility of production and (building) materials. This includes a recycling-oriented choice of materials and construction in building design as well as post-use strategies and waste avoidance. Furthermore, consistency can mean offering compensatory measures to counteract the damage to the natural systems of soil, water, air and biodiversity caused by construction.

In Germany, the construction industry is responsible for more than half of the total waste generated. In 2016, 222.8 million tonnes (54.1%) were attributable to construction and demolition waste. (Destatis, 2018). Of this, only about 34 % was recycled or recovered with a loss of quality. The rest was either used for backfilling or was disposed of in landfills (Kreislaufwirtschaft Bau, 2018). The goal of closed material loops is still far from being achieved in the building industry.
A sustainable use of resources and the closing of material loops to reduce waste and preserve the environment is an important task. The " Earth Overshoot Day", which indicates when the naturally generated resources of the earth are arithmetically used by humans, has been occurring continuously earlier since 1970. In 2019, humanity had already spent the resources available for the year on 29 July 2019, meaning that we lived the rest of the year at the planet's expense (Umweltbundesamt, 2019).

5.2 The building stock as a resource store - Urban Mining

A study published in 2015 calculated the volume and composition of the anthropogenic stockpile in Germany. Anthropogenic stockpiles are the resources bound by humans in products, buildings and infrastructures that are subject to constant change through production and disposal (Müller & Lehmann, 2017, S. 17).
For Germany alone, anthropogenic stocks amount to a mass of at least 28 billion tonnes. At 55%, building engineering accounts for the largest share of anthropogenic material stocks, closely followed by civil engineering, which accounts for 45%. The remaining percentage is accounted by consumer and capital goods and building services (Schiller, Ortlepp, & Krauß, 2015, S. 34).

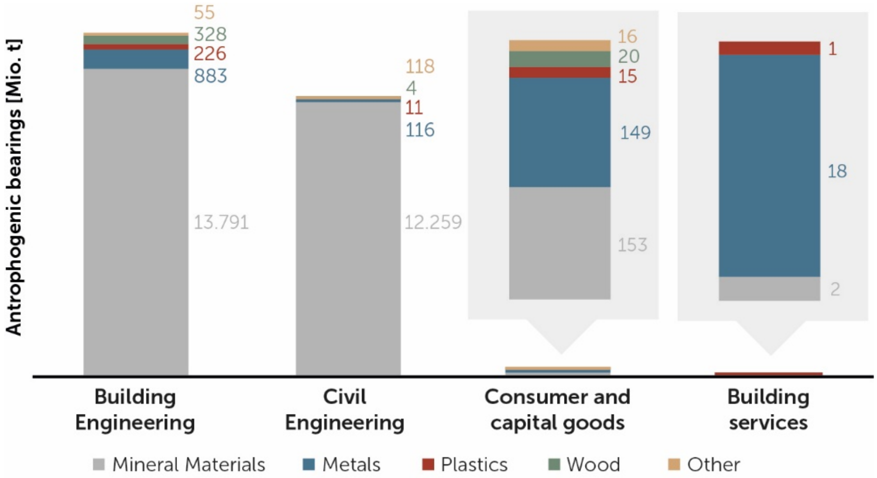

Figure 5-1: Anthropogenic stocks by goods groups and materials in Germany. Own illustration based on: (Müller & Lehmann, 2017, S. 32)

Demolitions and refurbishments are expected to increase strongly in the future. The reasons for this are demographic change and the steady emigration and shrinkage of many eastern German and, in some cases, western German towns and villages, as well as a change in housing needs. This will lead to a further increase in the amount of waste generated by construction (Müller & Lehmann, 2017, S. 50).
This needs to be seen as an opportunity and the potential of built-up materials from the urban mine needs to be recovered so that it can be used to construct new buildings.
The law anchoring a circular economy in Germany is given by the Waste Management Act (Kreislaufwirtschaftsgesetz), which was published in 2012. *„The purpose of the Act is to promote the circular economy to conserve natural resources and to ensure the protection of people and the environment in the generation and management of waste." (Author's translation, §1, Kreislaufwirtschaftsgesetz)*
In addition, raw materials should remain in the product cycle for as long as possible and as few primary raw materials as possible should be needed to close a product cycle (see Fig.).

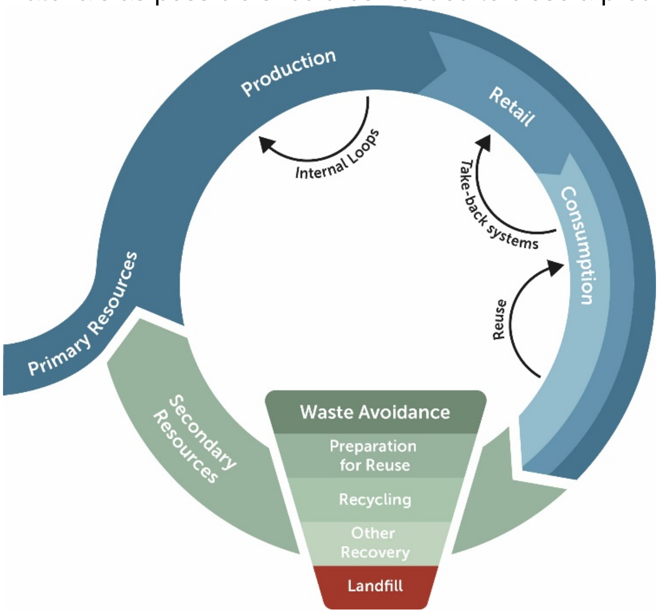

Figure 5-2: Model of the circular economy. Own illustration based on: (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2017)

The Waste Management Act defines a hierarchy according to which waste is to be avoided or managed (§3, Kreislaufwirtschaftsgesetz), Table 5-1.
In terms of the building industry, this means that the aim should be to use existing buildings for as long as possible and not to build new ones (1st priority). If a new building or, better, an extension of a building is planned, attention should be paid to circular planning in the choice of materials and construction structures,

and the proportion of secondary raw materials used should be maximised. This includes the planning of high-quality material recycling at the end of the building's life cycle.

Table 5-1: WASTE HIERARCHY

Avoidance	Avoiding disposal does not result in harmful effects for people and the environment caused by waste. Avoidance includes, among other things, an extension of product life, adapted consumption behaviour and the reuse of products.
Reuse	Reuse refers to the subsequent use of a product without dissolving the product form with the same use in another place for which it was initially intended.
Preperation for reuse	Preparation for reuse can be done by cleaning, testing or repairing products. The aim of the process is to reuse the building materials after preparation for the same purpose that the product had before removal.
Recycling [and downcycling]	According to the Waste Management Act (Kreislaufwirtschaftsgesetz), recycling refers to any recovery process that prepares materials for another use. This subsequent use can have the same purpose as the original material or serve a different purpose. Recycling according to this definition also includes downcycling, which denotes recovery at a lower product level.
Other recovery	Energy recovery, which is not possible with mineral construction waste, and backfilling are attributed to other recovery. This recovery requires the least effort, but is also the recovery with the lowest product level.
Disposal	A disposal is any process that is not a reuse and recovery. Thus, landfilling in particular is a waste disposal. In addition, incineration without energy recovery and backfilling without the need for construction can be classified as disposal.

A distinction can be made between the technological and the biotic loop in the recycling of materials. The technological loop describes an industrial processing of materials after deconstruction and sorting. The material loop is only considered closed if the secondary raw materials produced are of the same quality as the primary raw materials and if only negligible mass losses occur during their production. The processing and production of technical raw materials and components (e.g. metal) sometimes requires a large amount of energy, which has a negative impact on the CO_2 balance of the products. Compared to primary metal, however, RC metal is much more "energy-efficient". In the case of aluminium, the energy input in the first RC process is even reduced by 95% (Lonsinger, 2019). In addition, the extraction of non-renewable primary raw materials goes along with a destruction of the environment.
Biotic materials that are kept in the biotic loop can ideally be composted after a multi-stage cascade use. Thus, new plants are created from the nutrients, which can be processed into building materials after a growth phase. In practice, however, composting of biotic construction waste has not been envisaged so far, as no legal basis is provided yet. Biotic materials have the advantage that they bind as much CO_2 in the growth phase as they release in the later composting process or during energy recovery (Hillebrandt & Seggewies, Recyclingpotenziale von Baustoffen, 2019, S. 60f).

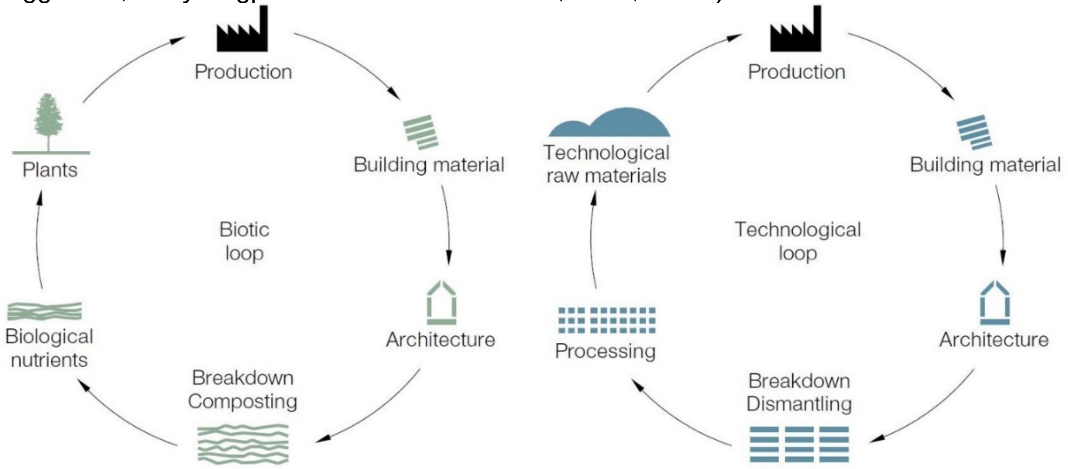

Figure 5-3: biotic and technological loop. Source: (Hillebrandt & Seggewies, Recyclingpotenziale von Baustoffen, 2019, S. 60)

5.3 Sustainability as a discipline in the Solar Decathlon

With the migration of the Solar Decathlon to Europe, the discipline of sustainability was included for the first time in the 10 judged disciplines of the competition. The relevance of the discipline is indicated by the points awarded (Fig. 4). In 2012, 2019 and 2021, 100 points of the 1000 total points represent an average competition of the decathlon. In 2010, the relevance of the sustainability competition was even higher with 120 points, but slightly lower in 2014 with 80 points.

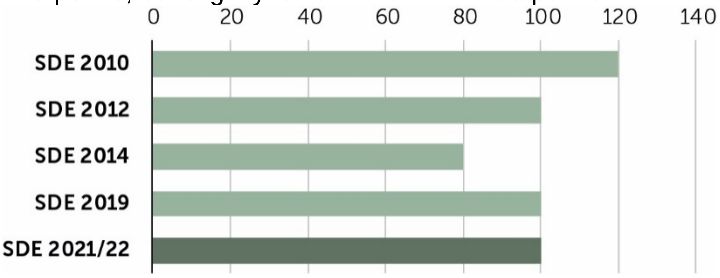

Figure 5-4: Number of points for the discipline of sustainability

With its introduction at the SDE 2010, the discipline was designed to be cross-disciplinary, just like the innovation discipline, which was also newly introduced (Fig. 5).

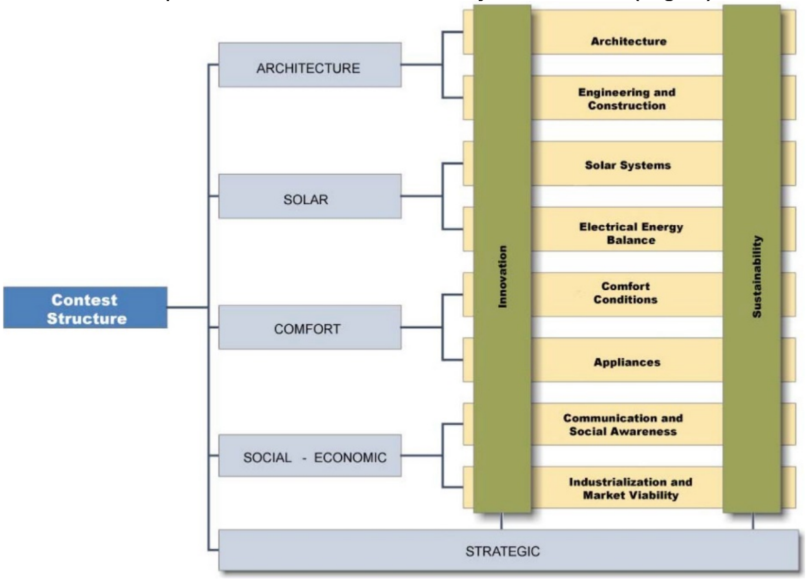

Figure 5-5: Competition structure 2010. Source: (SD Europe 2010, 2010)

This resulted in the content of the competition being thematically linked to the respective eight regular disciplines as follows, Table 5-2.

Table 5-2: TOPICS OF THE SUSTAINABILITY DISCIPLINE

Sustainability in…	**Criteria**
Architecture	Passive strategies to reduce energy requirements, optimised use of daylight, selection of materials according to ecological aspects and/or recycling and reuse
Technological Components of the house (Engineering and Construction)	Water consumption, life cycle, flexibility of the structure, possibility of reuse and adaptability to technical changes
Solar Systems	Assessment of the energy impact and CO_2 reduction potential of PV and solar thermal systems
Electrical Energy Balance	Degree of self-sufficiency and strategies for temporal correlation of generation and consumption
Comfort Conditions	Evaluation of strategies and systems to increase the efficiency of ventilation and humidity control, lighting, acoustics, air quality, heating, cooling. Durability/maintenance of systems
Appliances and Functioning	Evaluation of the efficiency of the electrical equipment
Communication and Social Awareness	Evaluation of the teaching of sustainability issues
Industrialization and Market Viability proposal	Criteria for industrial production of houses: Flexibility of use, maintenance requirements, assembly, disassembly, possibility of system expansion.

Due to the dependence on the other disciplines laid down in the competition rules, no clear and independent profile of the sustainability discipline emerged. This did not change with the subsequent competitions in Europe. The name as well as the exact definition of the competition objectives were revised slightly in each case, but the dependence on the other competition disciplines remained. As a result, the SDE as a whole has always covered the efficiency strategy very well through the many energy-related disciplines. However, the sustainability strategies of consistency and sufficiency were less considered.
With this in mind, the discipline of sustainability was redefined for the Solar Decathlon 2021. The dependency on the other disciplines no longer exists. The discipline covers in particular the consistency and sufficiency of the building design through two sub-contests, as the efficiency strategy is already represented by other disciplines.

- The sub-contest "Circularity" includes the evaluation of the loop potential of the building construction, i.e. the consistency strategy. This includes mapping the recycled content of materials, the detachability of construction joints, the longevity of materials as well as the recycling opportunities of materials after their life cycle. These parameters of circular construction are quantitatively measured and evaluated by the so-called "Urban Mining Index - UMI" tool (Rosen, 2020).
- The sub-contest "Sufficiency, Flexibility & Environmental Performance" covers a broad spectrum of sustainability aspects that pursue the strategies of sufficiency and consistency in particular. Measures to strengthen and preserve biodiversity as well as concepts to curb climate change, especially at the urban level, for example through microclimatic heat islands, are evaluated in the so-called "Urban-Loop-Design". In addition, concepts are called for that promote a sustainable society, contribute to increasing space efficiency and guarantee the longest possible durability of buildings through flexibility of use. Measures such as regional building material procurement, absence of pollutants or building biology are covered by the topic area of building material. (Hillebrandt & Müller, Urban-Loop-Design, 2020).

A life cycle analysis with regard to energy use and climate gas emissions over a period of 50 years is represented in the competition discipline "Engineering and Construction". Economic sustainability is covered in the discipline "Affordability &Viability".

5.4 Conclusion

The aim of the Solar Decathlon has always been to develop sustainable building concepts. The clear focus has ever been on the energy efficiency of the buildings. Sufficiency and consistency have played a very subordinate role in the competition rules, even in the discipline of sustainability. Nevertheless, some teams succeeded in placing circular construction and urban mining in the competition context. However, essential aspects for an assessment of circularity, such as the connection techniques of the individual material layers as well as a direct quantifiable comparability, were not available.
By redefining the sustainability discipline, the aim is to eliminate the deficits of past competitions and to improve the competition's overall profile in terms of sustainability. This is achieved by the newly developed tool "Urban Mining Index", which compares the circularity of the individual House Demonstration Units on the basis of calculated loop potentials of the building structures, taking into account the material joints. This is complemented by the new sub-discipline "Sufficiency, Flexibility & Environmental Performance", in which the teams are to present their sufficiency strategies.
The Solar Decathlon Europe thus becomes a research subject in which novel evaluation tools of sustainable construction are tested on realised projects. There is the chance to put concepts developed in a university context into practice on a small scale and to try out innovative ideas. The competition also offers the opportunity to present sustainable topics to a broad public and to spread them throughout the world.

5.5 Project Examples

In the following, project examples from the years 2010 to 2019 of the Solar Decathlon Europe are used, which have particularly pursued the concept of circular building. The "Building Energy Competition & Living Lab Knowledge Platform", where all documents of past Solar Decathlons are available, served as a source of information (Voss & Hendel, 2020).
In order to select the projects, the teams from each of the past four SDEs that were among the top five rankings in both the sustainability and architecture disciplines were determined. Nine teams met this entry criterion, which were then examined for pre-use and post-use strategies of material recycling on the basis of the Brief Reports.
Urban mining concepts are considered that have already reused existing components or relied on recycled secondary raw materials in the planning (pre-use). In addition, it is investigated to what extent urban mining design concepts exist that enable a later reuse of the components or a material recycling in the technical cycle or use renewable raw materials that can be kept in the biotic loop (post-use).

				Urban Mining Concept (Pre-Use)		Urban Mining Design (Post-Use)		
SDE	Team	Sustainability	Architecture	Reused	Recycled	Reuse	Recycling	Renewable materials
10	Armadillo Box	4	2				Plaster, interior wall panels, floor of the exterior living area made of **soil**, **steel** construction	**Wood** construction
12	Andalucia Team	2	4				Claimed high number of recyclable materials	e.g.: **Cork** and **wood**
12	Ecolar	4	4			**Exchange market** for the modules (low-cost productions or extensions)	85 % of the building e.g.: **Clay** building boards	e.g.: wooden box girders; **Wood** in floors, ceilings, terrace, window frames; **hemp insulation**
12	Med in Italy	1	3		Walls made of textile, filled with **sand, rubble or earth** (high thermal mass); Exterior flooring made of **recycled plastic** panels		**Kitchen unit** is 100 % recyclable	Building structure, pillars, foundations, floors and interior walls made of **wood**, **Wood fibre insulation** (compostable), **Hemp** (shading, façade cladding)
12	Counter Entropy	3	2	Platform under the house is a **construction site scaffolding**; **CD facade panels**, Wooden planks of the house from **wooden grandstand roofing** of an Aachen football stadium; Outside bench made from borrowed **beer crates**	Built-in furniture made of **wood** from **bulky waste** furniture and chipboard with production defects. Insulation from newspaper **cellulose flakes**	Platform under the house is a **construction site scaffolding**; Outside bench made from borrowed **beer crates**		**Wood** construction
14	Team Mexico Unam	3	4		Partial recycling shares (not explained in more detail)		**Steel frame** construction	Partly **wooden** construction
19	Habiter 2030	1	3		**Lime hemp insulation** Métisse insulation based on **recycled cotton**, **wood wool** insulation, **wood-based panels**		**Clay plaster, raw clay brick**	**Wood wool** insulation, **cotton** insulation, **Hemp lime** **Timber frame** construction
19	TO	3	3			The building is being reconstructed in several places		Renewable raw materials

Figure 5-6: Investigation matrix of circular building concepts

5.5.1 Ecolar – Team Constance SDE 2012

The "Ecolar" building of the Constance University of Applied Sciences team, certified with gold by the German Sustainable Building Council (DGNB), is characterised in particular by its modular reuse concept. An exchange platform for building modules is designed to ensure the reuse of modules after the utilisation phase. This module platform also enables flexible subsequent building adaptation through extensions with second-hand modules, which saves material, costs and working time.

Figure 5-7: Ecolar exterior view. Source: (Hochschule Konstanz, kein Datum)

The structure of the building is characterised by a timber frame construction into which 2.70 x 3.95 m wall modules are fitted. The "Ecolar" house consists of two types of façade modules:

- Translucent Multifunctional Facade elements (TMF): The translucent facade modules contain a wooden lamella structure between two glass panes to minimise solar heating, and are insulated by translucent aerogel, whose high-quality recycling at the end of the life cycle is questionable, however.
- Opaque Multifunctional Facade element (OMF): The opaque facade modules, on the other hand, feature hemp insulation. On the outer skin of wooden slats are mounted PV modules that serve to generate electricity for the building.

The roof and floor construction can also be expanded or deconstructed modularly in the construction grid to ensure the greatest possible flexibility and potential for further use (Team ecolar, 2012).

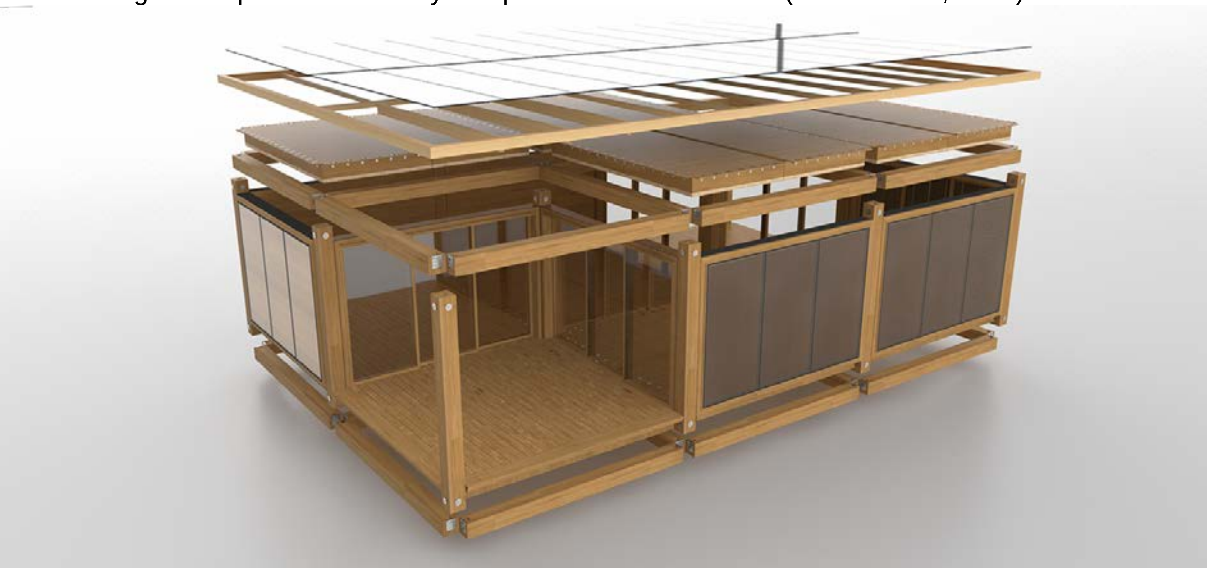

Figure 5-8: Ecolar modular construction, Source: (Hochschule Konstanz, kein Datum)

The concept of an exchange of building modules would only make sense under real conditions for a large number of buildings of the same construction. Examples of application would be, for example, large apartment buildings of the same structure, as was already the case with “Plattenbauten” (large panel system-building), or on a smaller scale with prefabricated houses.

5.5.2 Counter Entropy House – Team Aachen SDE 2012

The "Counter Entropy House" of the RWTH Aachen team features a high degree of reused or further used components and materials. The strategy of urban mining is consistently pursued with many examples and innovative ideas.

Figure 5-9: Counter Entropy House. Source: (DETAIL, 2012)

No longer used compact discs, which are increasingly being replaced by digital media, are further used as façade material. The CDs come from organised collection campaigns and recycling yards near Aachen. For recycling, the aluminium coating was mechanically removed from the polycarbonate CD blanks by a CD recycling company. To create translucent CD façade panels from these, the blanks were layered on top of each other and bonded in a single-material baking process without the use of adhesives.

Figure 5-10: Further used materials (right: wooden beams, left: CD façade). Source: (Team RWTH Aachen, 2012)

The wooden planks of the outdoor terrace and the interior consist of further used wooden beams from the grandstand roofing of a demolished football stadium in Aachen. The beams were tested for pollutants in advance to avoid health risks for students and visitors.
The "Counter Entropy House" and the adjacent wooden terrace are elevated by a rented construction site scaffold, which is used again for construction sites after the Solar Decathlon.
The final example of the urban mining carried out by the team from Aachen is the large built-in furniture that divides the large all-room into different zones. These consist largely of reused chipboard (Team RWTH Aachen, 2012).
All these urban mining strategies contribute to avoiding waste and minimising energy consumption and CO_2 emissions for the materials.

5.5.3 Habiter 2030 – Team Lille SDE 2019

The "Habiter 2030" team from Lille relies to a large extent on downcycled materials and materials that can be recycled. Downcycling describes the recycling of products that, as a new building material, cannot correspond to the same technical properties as the primary building product.
In the "Habiter 2030" house, biotic materials in particular are processed according to the principle of cascade use. Cascade use describes the principle of a step-by-step downcycling of building materials that cannot be recovered without a loss of quality, in order to delay the energy recovery of biotic building materials in a waste-to-energy plant as long as possible. On the one hand, the so-called Métisse insulation based on recovered cotton is used in the building, and on the other hand, wood wool from wood production residues is used.

Figure 5-11: Habiter 2030. Source: (République Francaise, 2019)

Particularly valuable for a closed material loop are recyclable building materials that can be recycled after use in the building structure without loss of quality and can be made available again as the same building material. Metals are a typical example of this type of recycling.
In the house of the team from Lille, recyclable materials are used to a large extent in the form of clay products. Unburnt clay bricks are integrated into the timber frame construction with the advantage of a high thermal mass. In addition, a lime-hemp-based base coat and clay-based finishing plasters are used. (HABITER2030, 2019).

Figure 5-12: Built-in clay bricks and lime-hemp-based underplastering, Source: (HABITER2030, 2019)

In addition to their high recycling potential, these recyclable products have the advantage that they can provide excellent building biology and good indoor air comfort.

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6. Heat Pump Systems

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6.1 General Relevance

Heat Pumps are a widely used technology for heat and cold supply in buildings enabling the use of environmental energy by the thermodynamic anticlockwise Carnot cycle. As environmental energy usually act ambient air, waste air near-surface geothermal energy, ground or sea water and solar thermal heat. In addition, heat pumps are used to utilize waste heat, low temperature heat from deep geothermal or within cold district heating networks. The majority of heat pumps are of the type electric driven compression and as such a heating and cooling technology which is coupling the sectors electricity and heat. In combination with PV and or wind and battery storage a high degree of energy autonomy can be achieved and a grid supportive operation delivered.

6.2 Relevance in Building Competitions & Living Labs

Looking at the technology used for heat and cold supply in the recent SD competitions since the early 2000s heat pumps was the must. All homes are “all electric”. On one hand this is a simplification for the teams and increases fairness, on the other hand, further technological options are. As long as small homes are in the focus, the limitation to heat pumps is reasonable, but for apartment buildings and urban situations, other options like district heating or cooling add to the heat pump scenario.

The energy performances of heat pump systems are highly depending on their system integration due to their temperature dependent performance. Thus in building competitions and living labs the focus should be less on the performance of the heat pump itself but on optimal system integration.

The performance (SPF and COP) of the heat pumps was not monitored in competitions up to now but has partly been addressed in living labs of the participating universities following the competition. Within the competition, the monitoring was limited to the power metering of the total HVAC circuit, but not more detailed and no heat output was monitored.

6.3 Parameters

The energy performance of a heat pump system is substantially determined by the temperature level of the heat source and the heat sink, thus temperatures have a considerable impact on the efficiency. There are a diverse range of factors that influence the operating temperatures, whereby it is not just the field of application of the heat pump that plays an important role but also the planning, installation, commissioning and operating phases. The field of application of a heat pump is limited to a certain extent by the availability of environmental energy and their temperature level, which has an impact as well on the chosen heat pump technology. In addition there are boundary conditions and limits in terms of the required sink temperatures: Example given there are relevant differences between the requirements in existing, non-refurbished buildings with radiators and in new buildings. In new buildings with floor heating, the heating operation differs considerably from the operation for domestic hot water heating. In multi-family buildings with a higher share of domestic hot water and higher requirements on pure water this is even more evident. Through their choice and size of heating system, design engineers determine the required heating circuit temperatures within the framework provided by the heating requirements and the spatial conditions.

6.3.1 Heat and Cold Delivery

Common Systems for heat and cold delivery are air intakes, recirculation and floor heating respective slab cooling systems. For heat delivery radiators are widespread as well. With air intakes and radiators delivery temperatures are generally higher than in floor heating, thus the latter is preferable. The higher time shift in floor heating systems has to be taken into account in the control.

6.3.2 Domestic Hot Water

Due to water quality a defined way to avoid unwanted contamination has to be defined – especially in larger systems with multiple distributed taps. The common and save solution is to keep system pure water temperatures over 60°C, which is critical regarding the energy performance of heat pumps. Innovative concepts like a combination of ultrafiltration and automatic tapping to avoid stagnancy allow the operation of the DHW System at lower temperatures and are thus favourable regard the performance [Kistemann2015].

6.3.3 Environmental sources

As environmental sources air and ground source heat pumps are the most common ones. Air source heat pumps are due to their stronger seasonal variation of the source temperature less performant but less expensive. Beside these two main technologies ground or sea water could be used as source, as well as waste heat e.g. heat exchanger in the sewage duct. Solar thermal collectors could act as source as well, a promising solution are combined PV and thermal collectors, especially those which could collect energy from the ambient air in times with no or low irradiation.

6.3.4 Installation

Careful installation, professional commissioning and controlled operation help to maintain the planned operating temperatures and adapt to any deviating requirements in practice. For example, a non-adjusted heating curve could mean that the system is operated with heating circuit temperatures that are higher than required. An unfavorable positioning of the storage temperature sensors can cause the storage tanks to be incorrectly charged, particularly with combined storage tanks: the heat pump then generates more energy at the high domestic hot water temperature level than is required. Not completely closing 3-way vents and missing check valves can cause undesired discharging of the domestic hot water storage tank. In addition to aspects that influence the operating temperature, the auxiliary energy for control also has to be taken into account.

6.4 Performance Indicators

The key performance indicators of a heat pump system are the following:

(i) The coefficient of performance (COP) of a heat pump is a characteristic of the heat pump itself and is determined in the steady state, i.e. under constant operating conditions. It indicates the ratio of the heating capacity to the electrical power consumption electrical power of the heat pump.

(ii) The seasonal performance factor (SPF) describes the ratio of the provided thermal energy to the consumed electrical energy over a longer period of time (e.g. one year).

6.4.1 Coefficient of performance (COP)

The anticlockwise Carnot cycle provides an ideal reference cycle for comparing heat pump processes. With the Carnot cycle, the efficiency is only dependent on the upper temperature T_U and the lower temperature T_L between which the cycle runs. Even if the coefficient of performance for a heat pump is considerably lower, its temperature dependence is still largely comparable with the reference cycle. The respective evaporation and condensation temperatures are therefore decisive for the efficiency of heat pumps as can be seen in the following equation:

$COP = \frac{\dot{Q}_H}{W} = \eta \times COP_{Carnot} = \eta \times \frac{T_U}{T_U - T_L}$ T in K.

The coefficient of performance COP is a characteristic of the quality of the Carnot cycle and is determined on test rigs with defined boundary conditions. For example, the B0/W35 operating point in accordance with EN 14511 is used as the rated standard operating point for brine-water heat pumps. This describes the operation with a brine temperature of 0 °C/-3 °C (input / output) and a heating circuit temperature of 35 °C/30 °C (output / input). When calculating the coefficient of performance in accordance with the standards, not only is the electrical power consumed by the compressor taken into account but also the electrical power consumed by the source pump and heating circuit pump in order to overcome internal pressure losses. Since the coefficient of performance considerably depends on the operating conditions, in particular the temperatures, it should only ever be specified and considered in relation to the operation conditions. In EN 14825 the SCOP (Seasonal COP) is defined, which gives an average COP under given conditions using a bin method.

6.4.2 Seasonal Performance Factor SPF

A general form to describe the SPF is the following: $SPF = \frac{\int_{t1}^{t2} \dot{Q}_H dt}{\int_{t1}^{t2} P_{el}\, dt}$.

The parameters influencing the seasonal performance factor of heat pumps are the timespan (usually a year or a month) and the chosen system boundaries. Fig. 1 depicts four possible system boundaries for a heat pump system:

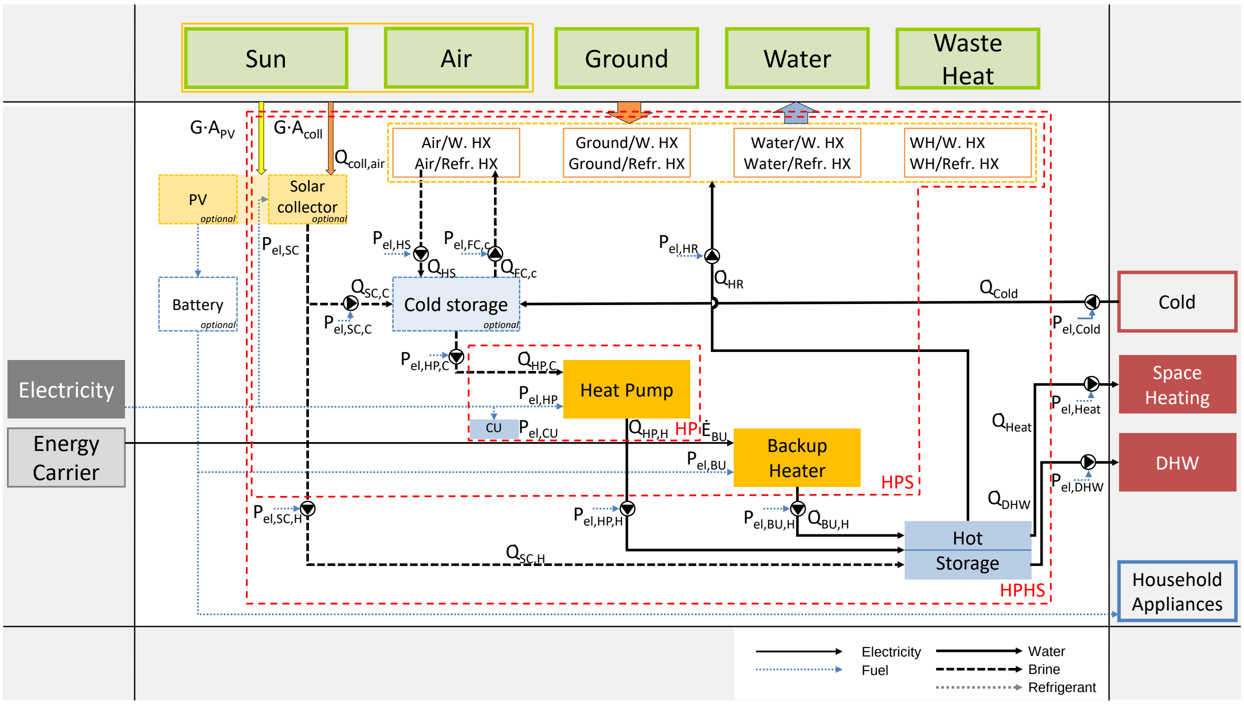

Figure 6-1:System boundary of a Heat Pump based heating system. In the upper part the environmental heat sources and sinks at site are shown, on the left side energy delivered to the site and on the right the net energy delivered to the building. Source: S. Herkel, Fraunhofer ISE based on [IEASHCT44]

The “narrowest” system boundary (HP) only includes the energy required by the heat pump unit (compressor, internal control system and, if required, an oil sump heating system for the compressor). If the heat source circuit’s ventilator, brine or well pump is also included in the balancing scope with supplementary electrical heating when installed this is described as a heat pump system (HPS). When balancing both the HP and the HPS, the thermal energy is determined directly behind the heat pump and/or the electrical back-up heater. When considering the efficiency of the entire heat pump heating system (HPHS), only the effective energy – i.e. behind the storage systems – is taken into account. In this case the charge pumps are also incorporated into the calculation as loads.

The following example shows graphically the temperature dependence of a heat pump with a COP of $3{,}8_{A2/W35}$ in a multi-family house (see Figure 6-2). In case 1, a high performance new building the share of domestic hot water is 40% and a DHW temperature of 45°C, in combination with floor heating, the SPF_{HP} is 40%*3,7+60%*5,4 = 4,7. In the second example (case 2), a partly retrofitted building with radiators and a share of DHW of 25% the SPF_{HP} is 25%*2,3+75%*3,6 = 3,3. Comparing these two examples shows a difference of 30% in the SPF suing the same heat pump and underlines the effect of the chosen system temperatures.

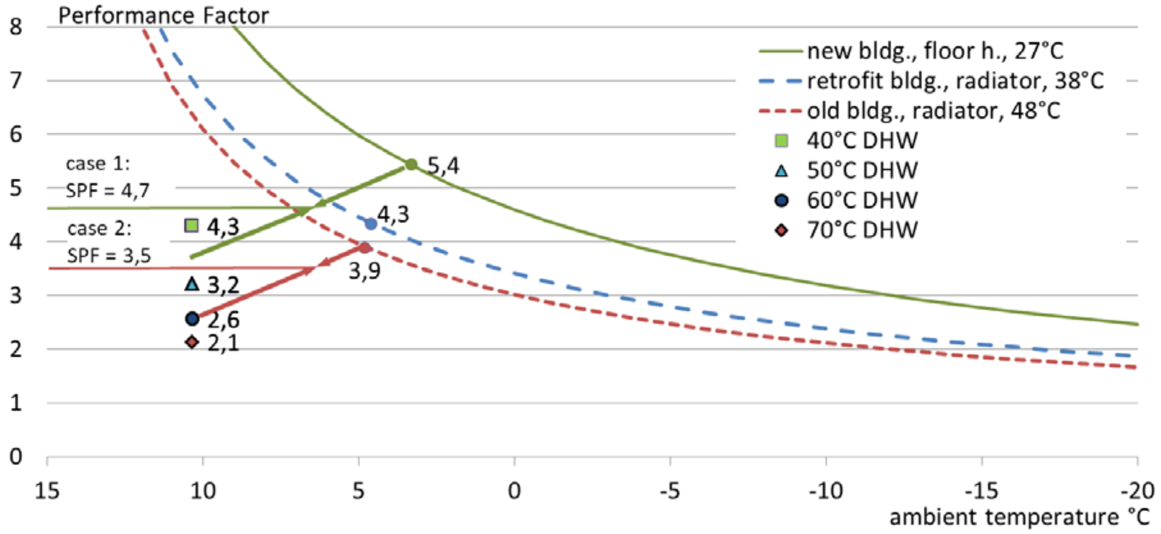

Figure 6-2: Performance factor of an air source heat pump depending on the ambient temperature. The markers show the annual average and thus the seasonal SPFHP. The SPF for the domestic hot water is related to the average ambient temperature of the whole year, for the heating related to the building dependent average ambient temperature in the heating season. Source: S. Herkel, Fraunhofer ISE

6.4.3 Assessment of heat pumps

The coefficients of performance of heat pumps enable different heat pumps from various manufacturers to be compared with one another - under the assumption that the coefficients of performance have been determined under the same boundary conditions. Likewise, a comparison of the results from different field tests or simulation is only possible to a limited extent if they have not used precisely the same balance boundaries and analysis methods. In addition to the issue as to where the system boundaries were defined, there are also other aspects that are relevant. For example, when calculating the seasonal performance factor it is a difference whether unused heating energy is taken into account that was produced in summer as a result of the system or as a result of faulty operation. It is also only possible to compare the same balancing periods with one another (e.g. one year).
In classifying the seasonal performance factor information, not only do the balance boundaries and the balance periods need to be specified but also the type of heating source, the application area (e.g. building standard, heating systems, ratio of the heating requirement to the domestic hot water requirement) and the operating temperatures. Quite often only the supply temperatures are specified as operating temperatures in the heating circuit. However, these are not the only ones that are decisive for the condensation temperature. The return temperature also has an impact.

6.5 Performance calculation and Simulation

For calculation of the SCOP the EN 14825 give a detailed method to assess the calculation of the annual performance based on a classification method. To calculate a heat-pump based heating systems in a more detailed way, there are manifold open source and commercial tools available with different degrees of detail. Heat pump models are available as part of large simulation packages like Energy Plus, ESP-r or Modelica, the latter gives the opportunity to extend your own models and compute even the thermo-hydraulic effects of specific refrigeration circuits.

6.6 Monitoring

As can be derived from the large variety of different boundaries and possible SPF values, there are many ways to monitor a HP system, ranging from very simple to rather complicated and detailed. Therefore, depending on the aim of the measurements also the complexity of the monitoring equipment and resulting from this also its costs can vary a lot. The easiest way to monitor a HP system would be to measure only the amount of produced useful heat for domestic hot water and space heating on the one hand, and the total electric energy consumption of the overall system on the other hand. By measuring these two values the performance factor SPF_{HP} or SPF_{HPHS+} (which includes additionally the electricity for the heating distribution pump) can already be determined in order to have a first hint for comparison of the systems' performances.
However, much more information can be derived from a more detailed measurement strategy. Depending on the main goal or interest of the investigation, different questions may be addressed. The performance factor SPF_{HPS} e.g. is very useful for the comparison of a SHP system with conventional heating systems as e.g. gas boilers as it does not consider storage losses. For any performance figure to be evaluated all energy flows have to be measured that cross the boundary corresponding to the respective performance figure's definition.
For model-based evaluation of complete systems, i.e. by means of simulation, or for the validation of numerical component models a more complex and highly differentiated monitoring strategy is required. Many heat flows and electricity consumers are to be covered and determined separately in order to have a detailed picture of the overall energy flows. As input for the validation of simulation models, also a relatively high frequency of data logging time steps is crucial e.g. collected data as mean values in a time frame between every one to five minutes.

6.7 Post Processing of Results from Simulation & Monitoring

The post processing of data could be seen as a two-step approach, first filtering and aggregation of data and second the visual representation of them. For comparison of different systems key performance indicators should be presented in a highly aggregated form. They are usually the mentioned performance indicator SPF with defined boundaries, the delivered heat and the electricity for compression, back-up heater and source pumps. For comparison as well the average temperatures on the condenser and evaporator side should be shown, see example from the German field test “WPsmart im Bestand” [Guenther2018].

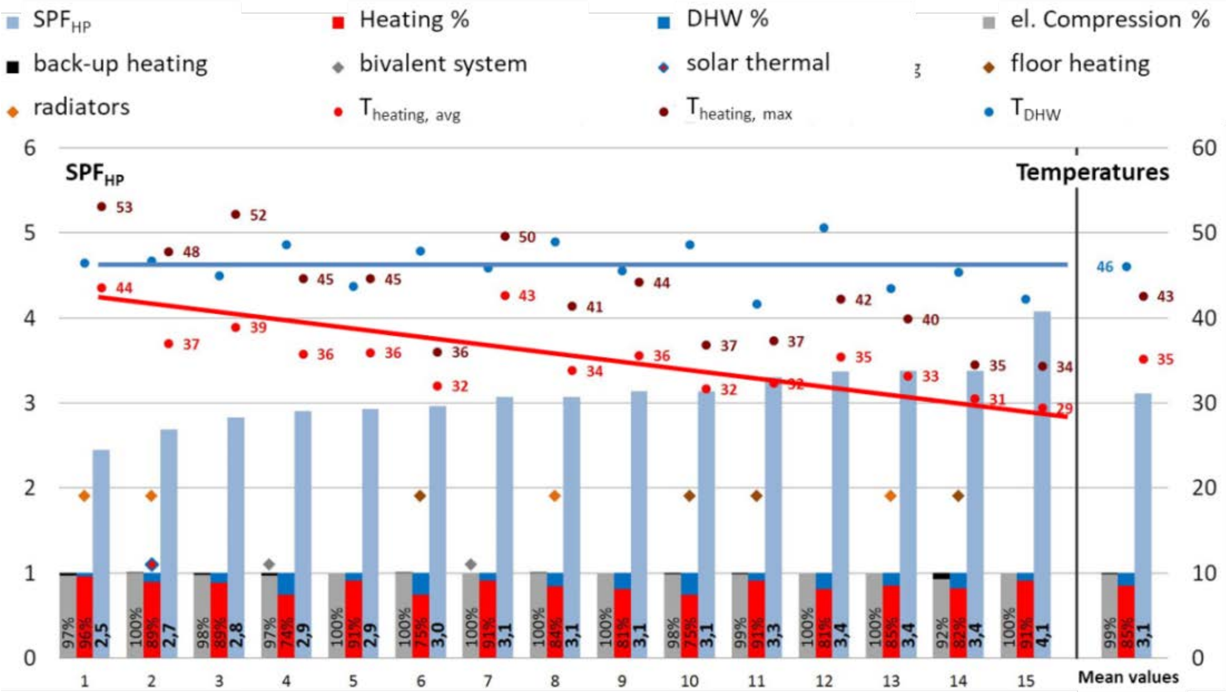

Figure 6-3: Comparison of the Seasonal Performance Factor SPFHP of 15 systems ordered by the performance. The dependency on the system temperatures can be seen clearly. Source: [Guenther2018]

As second example for a graphical representation of results a temperature analysis during the seasons of the in- and outlet temperatures of a ground source and their dependence on the ambient temperature is shown in Figure 6-4.

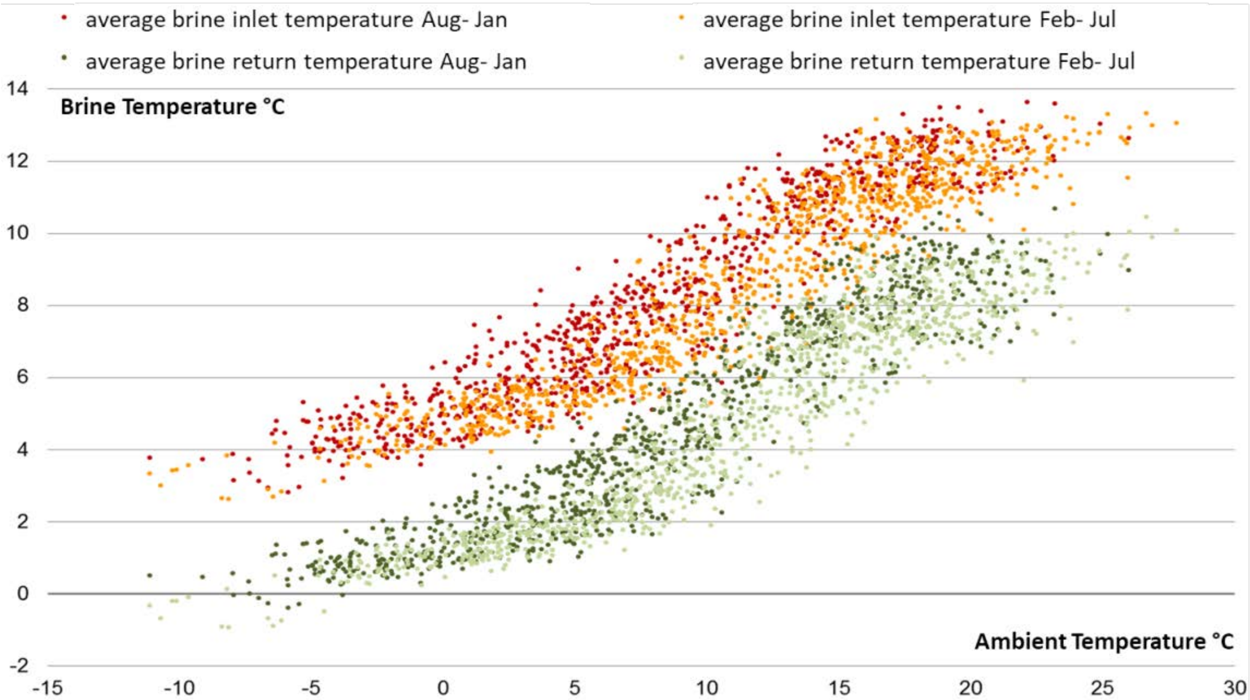

Figure 6-4: Inlet and outlet brine temperature of a ground source heat pump borehole heat exchanger. Using different colors, the seasonal time shift in the temperatures can be indicated (temperatures in the period August to January are higher due to the regeneration of ground in spring and summer) Source: [Miara2014]

6.8 Further Reading

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[IEAHPTA50] IEA HPT Annex 50 Heat Pumps in Multi-Family Buildings for Space Heating and DHW https://heatpumpingtechnologies.org/annex50/best-practices/

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7. Solar Thermal Systems

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7.1 General Relevance

Heat is the largest share of mankind's final energy consumption in all moderate climate regions of the earth, still largely dominated by space heating of buildings.
It is safe to assume that the necessary decarbonisation of our energy system will lead to a raising electrification of the heating sector, mostly driven by the installation of heat pumps that replace fossil boilers. This sector coupling (electricity - heat) in combination with energy storages will offer many opportunities for intelligent shifting of peaks in energy supply and demand profiles.
However, electrification alone is not yet the solution for a CO_2 free energy supply – this would imply that all electricity must come from renewable sources and be available all year round. That is a major challenge and it is reasonable to explore all available options that reduce the electricity load during the heating season. Solar thermal technologies are one means to do so.
Solar thermal collectors (flat plate collectors, vacuum tube collectors) are an attractive technology to provide solar heat for domestic hot water, space heating and low temperature process heat for industry (the latter will not be further elaborated in this context). In order to reach high solar shares, sufficiently large collector areas are necessary that charge a sufficiently large i.e. long term (seasonal) heat storage. Constraints are the availability of space (roof, façade, free land) for the mounting of collectors or missing heat storage capacity that will determine the need and dimensioning of an auxiliary heating.

7.1.1 Common solar thermal system designs

- Domestic hot water preparation – solar water heaters – for single and multi-family homes: Preparation of domestic hot water in single family homes was the starting point of commercialization of solar thermal technologies in the 1970s and 1980s. In most regions without need for space heating, thermosiphon solar water heaters nowadays are the most cost efficient and convenient technology for hot water preparation. In moderate climates, where ambient temperatures drop below freezing, pumped systems with freezing protection are state of the art. Most solar water heaters need an auxiliary backup heating to guarantee hot water production also during periods without sufficient solar irradiation. The typical dimensioning of solar water heating systems in moderate climates is such that Solar Heat covers about 60% of the total yearly energy consumption for water heating. Basically, all available heating technologies can be applied as auxiliary heating: Fossil or biomass fired boilers, CHP units, electrical heat pumps, electric resistance heating or district heating. The choice of the auxiliary has a high impact on the total CO_2 balance of the system, which means that the use of fossil fired boilers will have to phase out in the near future, even if used in combination with solar water heaters. For any electricity driven auxiliaries, it has to be kept in mind that the source of electricity generation, whether from renewable or from fossil generation, determines the CO_2 impact of the total system.
- Domestic hot water and space heating for single and multi-family homes: Solar thermal systems can deliver a share or even completely cover the energy demand for domestic hot water and space heating in single and multi-family homes. The dimensioning of a solar thermal system that aims for full coverage has to compromise the two extrema that either the collector field needs to be large enough that it can cover the heat demand in winter or the storage needs to be large enough that it can save heat that was generated in summer or autumn to the heating season. There are good examples of such systems but still the most common dimensioning of solar thermal systems for

space heating is much less ambitious: depending on the building standard, so called combi-systems cover about 20 - 35% of the yearly energy demand for space heating and domestic hot water preparation. The major share of energy is provided by a conventional boiler or heat pump and, similar to the case of pure solar water heaters, this conventional heating system dominates the total CO_2 impact of the overall system.

7.1.2 New solar thermal system concepts

Apart from the above mentioned established solar thermal systems, that in recent years faced a market decline due to competition with photovoltaics, we see a variety of new solar thermal system concepts that evolved over the past years:

- Solar Assisted District Heating: Solar assisted district heating networks became popular initially in Denmark and then other countries like Germany, Austria and China. The solar collectors are typically installed in large units on free land. Some concepts foresee a large seasonal (pit or borehole) heat storage and thus achieve solar shares of the total heat demand well above 50%. Even concepts with over 90% have been demonstrated [01]. Other concepts only cover the summer load of a heat grid while the major load during the heating season is covered by a central (e.g. biomass fired) boiler [02]. Solar district heating grids with large seasonal storages are often combined with heat pumps that discharge the stores to low temperatures in wintertime 802. This combination increases the usable capacity of the store and enhances the efficiency of solar collectors. The lowest solar heat generation cost can be reached with large installations on free land, but solar collectors can also be integrated in a decentralized way, distributed on buildings' roofs that are connected to the grid.
- Solar thermal collectors in combination with heat pumps: The combination of solar thermal collectors and electrical heat pumps can be realized in parallel or in series. For parallel installation, whenever the solar radiation is sufficient the solar thermal collectors relieve the heat pump from generating high temperatures needed for domestic hot water preparation, which raises the average heat pump efficiency for the total of hot water and space heating [04]. In serial installation the solar thermal collectors serve as a direct heat source for the heat pump. If additionally, the solar collectors are good heat exchangers to the ambient air (this is typically the case for uncovered collectors) they may even serve as a heat source during night [05]. Other options for using solar heat as source for a heat pump use a storage medium to provide higher temperatures for the heat pump and to overcome periods with snow cover on the collectors. These are e.g. ground source and ice storage systems with active regeneration by solar collectors.

7.2 Relevance in Building Competitions & Living Labs

The relevance of heating systems for our energy system and its impact on CO_2 emission reduction is difficult to integrate into a building competition. The inclusion of the total system beyond the living lab itself can only be evaluated by system simulation. Also the integration of heating systems other than direct electric heating into a living lab can be quite complex and demanding. This is why in the past editions of SDE solar thermal collectors were used, if at all, then almost exclusively for domestic hot water preparation. They were usually not used for space heating.

Both, for new buildings as well as in renovation projects, it is desirable to make use of all suitable areas of the building envelope for the installation of solar components (PV and Solar thermal). Especially for solar thermal components the integration into the façade and roof areas are challenging from an architectural and functional perspective.

For SDE21 the hydraulic concept and integration with heat storage and auxiliary heat sources (if not 100% solar) needs to be designed for a multifamily building in an urban environment. The lab conditions however require a functional hydraulic installation that represents an excerpt of the complete system.

As an example, it can be imagined demonstrating the installation of façade or roof integrated collectors that shall be used as a heat source of a heat pump in combination with an ice storage. For the lab conditions, electrical resistance heating could simulate the heat pump and a smaller sensible heat storage could represent the ice storage. Still a complete hydraulic system would be installed to determine the collector field performance.

7.3 Simulation

Dynamic system simulation is a convenient and reliable way to evaluate the overall performance of a building and its heating system. Several simulation environments are available for thermal and hydraulic system simulation. TRNSYS, Polysun, T-Sol, E-Plus are among the most widely used programs.
All auxiliary heat sources, ambient conditions, heat storage and hydraulics are relevant for the system simulation, even if they will not be part of a living lab installation.
The following graph shows exemplary simulation results of temperatures over the height of a large thermal storage in a multifamily building in Switzerland that is heated by a large solar thermal collector field in combination with a PV-heat pump system [06].

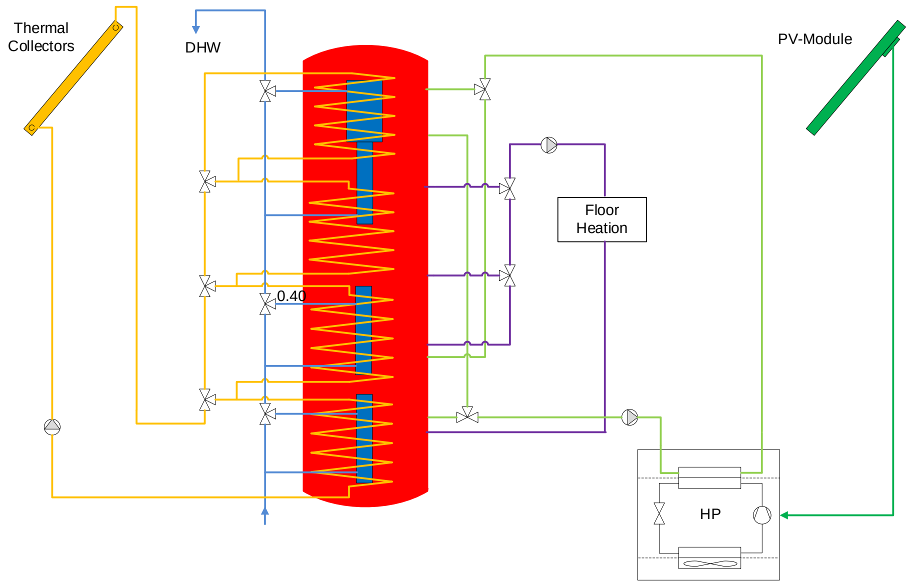

Figure 7-1: Schematic design of a solar thermal system with integrated large storage, PV-system and heat pump.

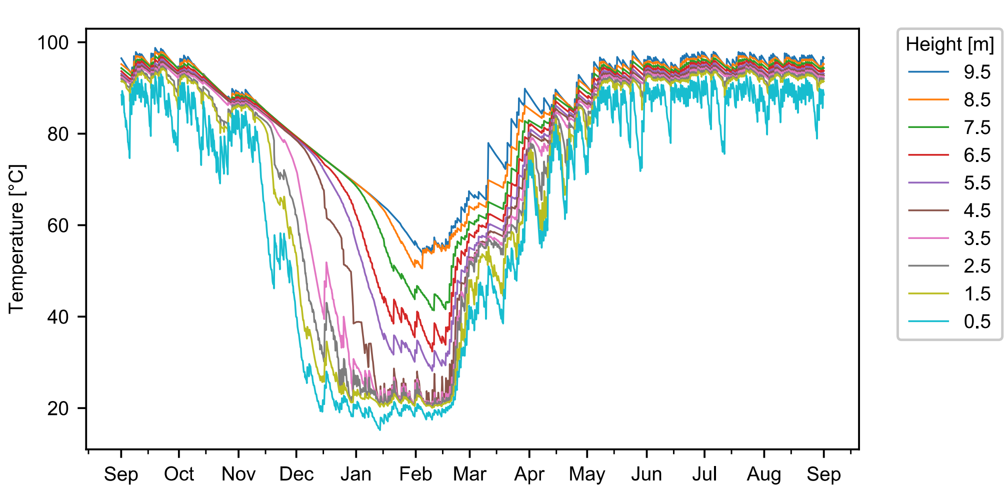

Figure 7-2: Simulated temperatures in the storage tank. System: 120 m^2 solar collectors, 88 m^3 storage, 40m^2 PV, 10kW heat pump:

7.4 Performance indicators

In principle, a big variety of performance indicators can be determined on component and system level. The goal from an energy perspective is of course to replace all CO_2 producing external energy supply for domestic hot water and space heating. The following Key Performance Indicators (KPI) apply for the complete solar thermal system, including the auxiliary heating and must be evaluated over the year on a monthly basis:

- Final energy consumption that is not produced on site.
- Solar share = 1 – final energy consumption / total energy consumption

The following graph gives the marginal final energy consumption for the system above with varied size of the storage (110, 99, 88 m³).

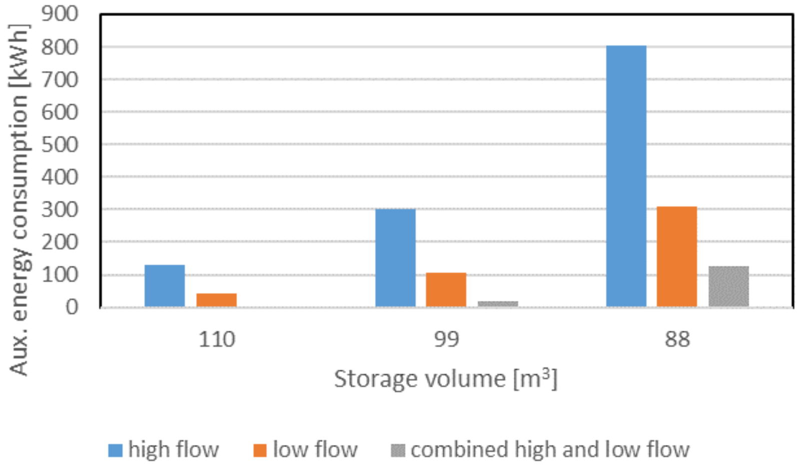

Figure 7-3: Auxiliary energy needed for different storage sizes and operation modes

7.5 Monitoring

Pilot and demonstration installations of innovative solar heating systems need performance monitoring over a relevant time i.e. one or several heating periods. The data acquisition system shall measure all relevant energy fluxes with sufficient time resolution (solar irradiation, heat flux from collector to storage, from storage to user, from auxiliary to storage, …). If relevant for the systems performance it will be necessary to monitor temperatures (room, heat storage, supply and return of heating and domestic hot water circulation). Also, the status of the control of the system and finally the influence of the users (water consumption, ventilation habits, window shading, …) must be documented.

In Figure 7-4 the main energy fluxes are shown for a real case in Switzerland. Measuring all main fluxes allows to analyse the performance of each component and the whole system. Further, a detailed measurement concept helps to optimize the components and their integration into the whole system. By measuring the energy fluxes with energy meters also the power, flow and temperatures should be analysed in detail. Important are also the parameters that influence the demand side of the building. These are the set-point room temperature, the user behaviour regarding window opening, blind use for window shading and the domestic hot water demand. These three factors can have a major impact on the system and have to be reported or measured.

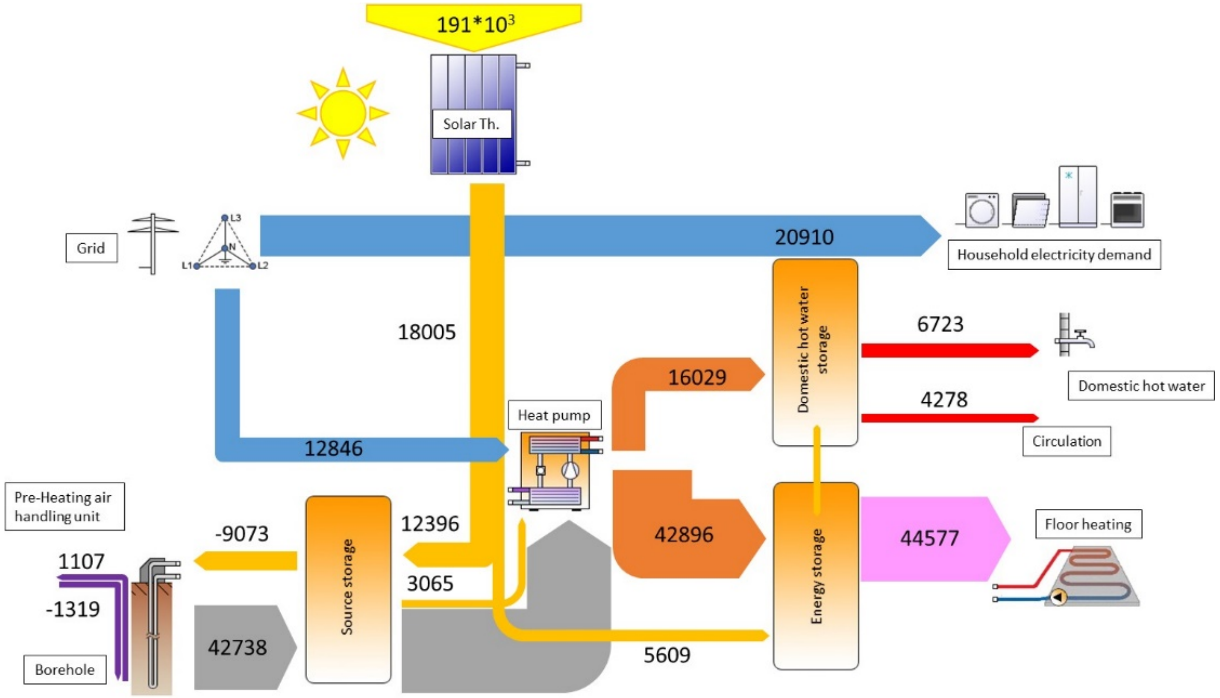

Figure 7-4: Energy flow chart for a real multifamily building with a heat pump and solar thermal collectors in Switzerland. All energy values are measured by energy meters in kWh [07].

At SDE21, the hydraulic installation of the living lab is to be integrated into a fully functioning system. The system might include components that are special to the lab conditions (e.g. a thermal storage that might be smaller for the lab conditions than it would be in the real system for a complete multifamily building). Still it is required to monitor and evaluate the performance of the lab system under lab conditions.

7.6 Post Processing of Results from Simulation & Monitoring

The goal of post processing is to derive performance indicators (see above) from simulation and/or monitoring data. Simulation and monitoring are mutually beneficial in the following sense:
Monitoring data often have gaps in the time series and might not cover a full year. In addition, they typically don't represent standard conditions of weather data or user profiles. This is where system simulation can step in to post process monitoring data and transfer them to adjusted boundary conditions or to complement gaps in time series. See IEA SHC Task 44 for further details on boundary conditions for building simulation [08].
On the other hand, simulation data build on assumptions like individual components' performances or user behaviour that in real live might be different than assumed [09]. Thus, monitoring data can help adjust boundary conditions and thus improve the reliability of simulation data.

7.7 Further Reading

[01] Sibbitt B, McClenahan D, Djebbar R, Thornton J, Wong B, Carriere J, et al. The Performance of a High Solar Fraction Seasonal Storage District Heating System – Five Years of Operation. Energy Procedia 2012;30:856–65. https://doi.org/10.1016/j.egypro.2012.11.097.

[02] Descheintre L., Huther H, Case Study: SDH Bioenergiedorf Büsingen (Germany), SDH, 2018, https://www.solar-district-heating.eu/wp-content/uploads/2018/05/DE_D3.1_Büsingen_EN.pdf

[03] Bauer D., Heidemann W., Müller-Steinhagen H.; DER ERDSONDEN-WÄRMESPEICHER IN CRAILSHEIM, OTTI, 17. Symposium Thermische Solarenergie, 2007, Kloster Banz, Bad Staffelstein

[04] Daniel Carbonell, Michel Haller, Elimar Frank, 2014. Potential Benefit of Combining Heat Pumps with Solar Thermal for Heating and Domestic Hot Water Preparation. In: ISES Solar World Congress 2013, 57, p. 2656-2665, 2014. https://doi.org/10.1016/j.egypro.2014.10.277

[05] Igor Mojic, Michel Haller, Bernard Thissen, Elimar Frank, 2014. Heat Pump System with Uncovered and Free Ventilated Covered Collectors in Combination with a Small Ice Storage. In: International Conference on Solar Heating and Cooling for Buildings and Industry (SHC) 2013, 48, p. 608-617, 2014. https://doi.org/10.1016/j.egypro.2014.02.071

[06] Lichtensteiger F, Ruesch F, Battaglia M, Haller M. Vollständig solar beheizte MFH mit saisonalem Wasserspeicher, Solarthermie, PV und Wärmepumpe, Kloster Banz, Bad Staffelstein, Germany, 2020

[07] Vassella et al., "Drei Unterschiedliche Innovative Solarunterstützte Wärmeerzeugungssysteme Für Drei Identische Minergie A-Gebäude.", SFOE Final Report, Switzerland, 2020, https://www.aramis.admin.ch/Texte/?ProjectID=36752

[08] Michel Y. Haller, Ralf Dott, Jörn Ruschenburg, Fabian Ochs, Jacques Bony, The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38 Part A: General Simulation Boundary Conditions, 2013, https://task44.iea-shc.org/Data/Sites/1/publications/T44A38_Rep_C1_A_BoundaryConditions_Final_Revised.pdf

[09] Igor Mojic, Meta Lehmann, Stefan van Velsen, Michel Haller, 2019. ImmoGap – Analysis of the performance gap of apartment buildings. In: E3S Web Conf. CLIMA 2019 Congress, 111, 2019. https://doi.org/10.1051/e3sconf/201911104016

8. Photovoltaic Thermal Systems (PVT)

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8.1 General Relevance

Photovoltaic-thermal PVT collectors convert solar energy into heat and electricity by combining PV modules and solar thermal collectors. In typical constructions, these hybrid solar collectors thermally couple PV cells to a heat transfer medium. The PV cells absorb the solar energy and generate an electric current, while the excess heat, which remains unused in PV modules, is transferred to a heat transfer fluid. This useful heat can, for example, be utilized to drive a heat pump, to charge hot water storage, or to heat air. By combining the generation of solar electricity and heat in a single component, PVT collectors can achieve a higher overall efficiency and a better utilization of the solar resource than conventional PV modules. Thus, more energy can be harvested per square meter of available roof or façade area, which makes PVT particularly interesting for densely-populated urban areas and plus-energy buildings. Furthermore, PVT collectors can generate cold by means of passive radiative cooling or by active air-conditioning, e.g. with reversible heat pumps, where PVT collectors act as heat dissipator. On the downside, PVT collectors typically achieve lower thermal efficiencies and thus lower heat gains and operation temperatures than flat plate or vacuum tube collectors. As a result, PVT systems have to carefully match PVT collector technology to the heat application with respective temperature levels.
Significant research has been put into developing PVT collectors since the 1970's. However, only in recent years, PVT collectors gained a significant market share. According to the report *"Solar Heat Worldwide 2020"*, the total area of installed collectors amounted to 1.16 million square meters in 2019. Uncovered water collectors had the largest market share (55 %), followed by air collectors (43 %) and covered water collectors (2 %). The country with the largest installed capacity was France (42 %), followed by Korea (24 %), China (11 %) and Germany (10 %).[5] Compared to the vast markets of PV and solar thermal, PVT collectors can be still considered a niche market, while gaining momentum most likely due to the drop of PV prices.

8.2 PVT Technologies

8.2.1 Types of PVT collectors

The different PVT collector technologies differ substantially in their collector design and heat transfer fluid and address different applications ranging from low temperature heat below ambient up to high temperature heat above 100 °C.[6] A typical layout is exemplary shown in Figure 8-1:

[5] Weiss, Werner; Spörk-Dür, Monika (2020): Solar Heat Worldwide 2020 Edition. Global Market Development and Trends in 2019 / Detailed Market Figures 2018. In IEA Solar Heating & Cooling Programme, AEE INTEC.

[6] Zondag, H. A.; Bakker, M.; van Helden, W. G. J. (2006): PVT Roadmap - A European guide for the development and market introduction of PV-Thermal technology.

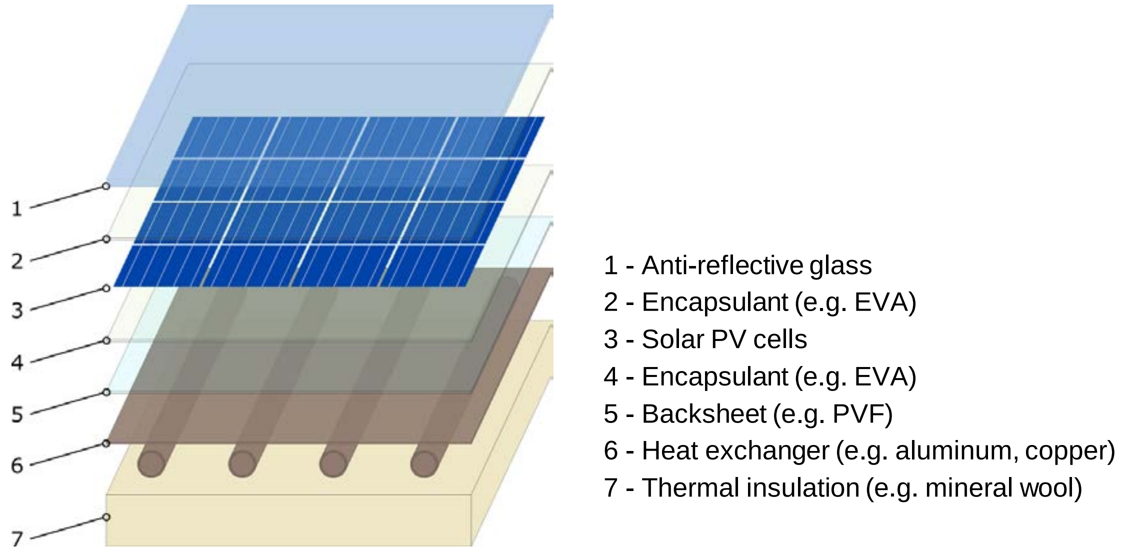

Figure 8-1: Schematic cross section of an uncovered PVT collector a sheet-and-tube type heat exchanger and rear insulation.[7]

There are a multitude of technical possibilities to combine PV cells and solar thermal collectors. A number of PVT collectors are available as commercial products, which can be divided into the following categories according to their basic design and heat transfer fluid (see Figure 8-2):

- PVT liquid collector
- PVT air collector

In addition to the classification by heat transfer fluid, PVT collectors can also be categorized according to the presence of a secondary glazing to reduce heat losses and the presence of a device to concentrate solar irradiation:

- Unglazed PVT collector (WISC)
- Glazed PVT collector
- Concentrating PVT collector (CPVT)

Moreover, PVT collectors can be classified according to their design, such as cell technology, type of fluid, heat exchanger material and geometry, type of contact between fluid and PV module, fixation of heat exchanger, or level of building integration (BIPVT, building integrated PVT collectors).[8]

The design and type of PVT collectors always implies a certain adaption to operating temperatures, applications, and giving priority to either heat or electricity generation. For instance, operating the PVT collector at low temperature leads to a cooling effect of PV cells compared to PV modules and therefore an increase of electrical power. However, the heat also has to be utilized at low temperatures.

The maximum operating temperatures for most PV modules are limited to less than the maximum certified operation temperatures (typically 85 °C). Nevertheless, two or more units of thermal energy are generated for each unit of electrical energy, depending on cell efficiency and system design.

[7] Image by Manuel Lämmle - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=8826741

[8] Brottier, Laetitia (2018). Optimisation biénergie d'un panneau solaire multifonctionnel : du capteur aux installations insitu. Mécanique[physics.med-ph].UniversitéParis-Saclay,2019. https://tel.archives-ouvertes.fr/tel-02133891

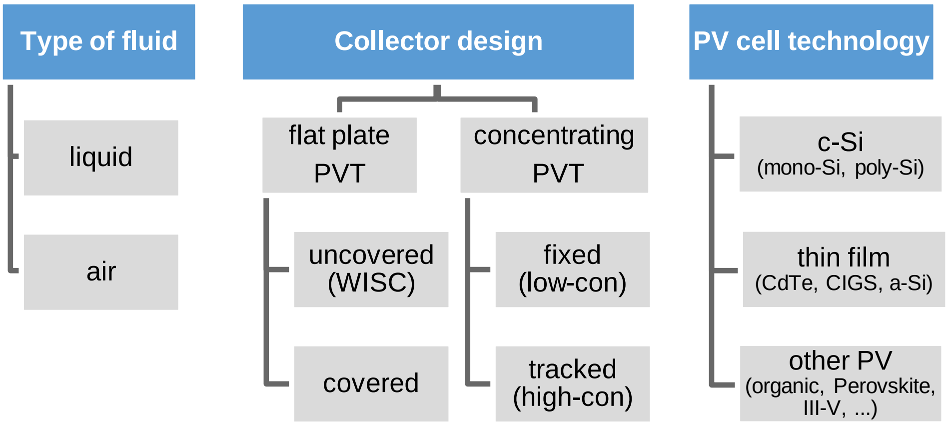

Figure 8-2: Classification of PVT collector technologies.[9]

8.2.2 PVT liquid collector

The basic water-cooled design uses channels to direct fluid flow using piping attached directly or indirectly to the back of a PV module. In a standard fluid-based system, a working fluid, typically water, glycol or mineral oil, circulates in the heat exchanger behind the PV cells. The heat from the PV cells is conducted through the metal and is transferred to the working fluid (presuming that the working fluid is cooler than the operating temperature of the cells).

8.2.3 PVT air collector

The basic air-cooled design uses either a hollow, conductive housing to mount the photovoltaic panels or a controlled flow of air to the rear face of the PV panel. PVT air collectors either draw in fresh outside air or use air as a circulating heat transfer medium in a closed loop. The heat transfer properties of air is lower than that of typically used liquids and therefore requires a proportionally higher mass flow rate than an equivalent PVT liquid collector. The advantage is that the infrastructure required has lower cost and complexity.

The heated air is circulated into a building HVAC system to deliver thermal energy. Excess heat generated can be simply vented to the atmosphere. Some versions of the PVT air collector can be operated in a way to cool the PV panels to generate more electricity and assist with reducing thermal effects on lifetime performance degradation.

A number of different configurations of PVT air collectors exist, which vary in engineering sophistication. PVT air collector configurations range from a basic enclosed shallow metal box with an intake and exhaust up to optimized heat transfer surfaces that achieve uniform panel heat transfer across a wide range of process and ambient conditions. PVT air collectors can be carried out as uncovered or covered designs.[Fehler! Textmarke nicht definiert.]

8.2.4 Uncovered PVT collector (WISC)

Uncovered PVT collectors, also denoted as unglazed or wind and/or infrared sensitive PVT collectors (WISC), typically comprise of a PV module with a heat exchanger structure attached to the back of the PV module. While most PVT collectors are prefabricated units, some products are offered as heat exchangers to be retrofitted to off-the-shelf PV modules. In both cases, a good and longtime durable thermal contact with a high heat transfer coefficient between the PV cells and the fluid is essential.[10]

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[9] Graph adapted from Lämmle, Manuel (2018): Thermal management of PVT collectors - development and modelling of highly efficient PVT collectors with low-emissivity coatings and overheating protection. PhD thesis, Fraunhofer ISE, INATECH Albert-Ludwigs-Universität Freiburg. doi: 10.6094/UNIFR/16446.

[10] Adam, Mario; Kramer, Korbinian; Fritzsche, Ulrich; Hamberger, Stephan (2014): Abschlussbericht PVT-Norm. Förderkennzeichen 01FS12035 -„Verbundprojekt: Standardisierung und Normung von multifunktionalen PVT Solarkollektoren (PVT-Norm)“.

The rear side of the uncovered PVT collector can be equipped with thermal insulation (e.g. mineral wool or foam) to reduce heat losses of the heated fluid. Uninsulated PVT collectors are beneficial for operation near and below ambient temperatures. Particularly uncovered PVT collectors with increased heat transfer to ambient air are a suitable heat source for heat pump systems. When the temperature in the heat pump's source is lower than the ambient, the fluid can be heated up to ambient temperature even in periods without sunshine.

Accordingly, uncovered PVT collectors can be categorized into:

- Uncovered PVT collector with increased heat transfer to ambient air
- Uncovered PVT collector without rear insulation
- Uncovered PVT collector with rear insulation
- Uncovered PVT collectors can be also used to provide renewable cooling by dissipating heat from a fluid via the PVT collector to the ambient air or utilizing the radiative cooling effect. Thus cold air or water is harnessed.

8.2.5 Covered PVT collector

Covered, or glazed PVT collectors, feature an additional glazing, which encloses an insulating air layer between the PV module and the secondary glazing. This reduces heat losses and increases the thermal efficiency. Moreover, covered PVT collectors can reach significantly higher temperatures than PV modules or uncovered PVT collectors. The operating temperatures mostly depend on the temperature of the working fluid. The average fluid temperature can be between 25 °C in swimming pool applications to 90 °C in solar cooling systems (Figure 8-3).

Covered PVT collectors resemble the form and design of conventional flat plate collectors or evacuated vacuum tubes. Yet, PV cells instead of spectrally-selective absorber coatings absorb the incident solar irradiance and generate an electrical current in addition to solar heat.

The insulating characteristics of the front cover increase the thermal efficiency and allow for higher operating temperatures. However, the additional optical interfaces increase optical reflections and thus reduce the generated electrical power. Anti-reflective coatings on the front glazing can reduce the additional optical losses.[11]

8.2.6 Concentrating PVT collector (CPVT)

A concentrator system has the advantage to reduce the photovoltaic (PV) cell area needed. Therefore it is possible to use more expensive and efficient PV cells, e.g. multi-junction photovoltaic cells. The concentration of sunlight also reduces the amount of hot PV-absorber area and therefore reduces heat losses to the ambient, which improves significantly the efficiency for higher application temperatures.

Concentrator systems often require reliable control systems to accurately track the sun and to protect the PV cells from damaging over-temperature conditions. However, there are also stationery PVT collector types that use non-imaging reflectors, such as the Compound Parabolic Concentrator (CPC), and do not have to track the sun.

Under ideal conditions, about 75 % of the sun's power directly incident upon such systems can be gathered as electricity and heat. For more details, see the discussion of CPVT within the article for concentrated photovoltaics.

A limitation of high-concentrator (i.e. HCPV and HCPVT) systems is that they maintain their long-term advantages over conventional c-Si/mc-Si collectors only in regions that remain consistently free of atmospheric aerosol contaminants (e.g. light clouds, smog, etc.). Power production is rapidly degraded because 1) radiation is reflected and scattered outside of the small (often less than 1°-2°) acceptance angle of the

[11] Zondag, H.A. (2008): Flat-plate PV-Thermal collectors and systems: A review. In: Renewable and Sustainable Energy Reviews 12 (4), S. 891–959.

collection optics, and 2) absorption of specific components of the solar spectrum causes one or more series junctions within the MJ cells to underperform. The short-term impacts of such power generation irregularities can be reduced to some degree by including electrical and thermal storage in the system.

8.3 PVT Applications

The range of applications of PVT collectors, and in general solar thermal collectors, can be divided according to their temperature levels: [12]

- low temperature applications up to 50 °C
- medium temperature applications up to 80 °C
- high temperature applications above 80 °C

Low temperature applications include heat pump systems and heating swimming pools or spas up to 50 °C. PVT collectors in heat pump systems act either as low temperature source for the heat pump evaporator or on the load side to supply medium temperature heat to a storage tank. Moreover, regeneration of boreholes and ground source heat exchangers is possible.[1] Uncovered PVT collectors with enhanced air-to-water heat exchange can even comprise the only source of a heat pump system. In combination with a system architecture allowing to store cold produced with WISC or air collectors also air conditioning is possible.

Low and medium temperature applications for space heating and domestic hot water provision are found in buildings, with temperatures from 20 °C to 80 °C. The temperatures of the specific system depend on the requirements of the heat supply system for domestic hot water (e.g. freshwater station, temperature requirements for legionella prevention) and for space heating (e.g. underfloor heating, radiators). Moreover, the PVT collector array can be dimensioned to cover only smaller fractions of the heat demand (e.g. hot water pre-heating), thus reducing operating temperatures of the PVT collector.

Process heat includes a diverse range of industrial applications with low to high temperature requirements (e.g. solar water desalination, solar cooling, or power generation with concentrating PVT collectors).[13] PVT collector technologies can be clustered according to their temperature level in the same way: the suitability per temperature range depends on the PVT collector design and technology. Therefore, each PVT collector technology features different optimal temperature ranges.

Figure 8-3 shows typical temperature ranges of both PVT applications and collector technologies. The operating temperature of the PVT applications ultimately defines the suitability of each type of PVT collector technology.

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12 Kalogirou SA (2014). Solar energy engineering: processes and systems. Second Edition. Academic Press. doi:10.1016/B978-0-12-374501-9.00014-5

13 Wiesenfarth M, Philipps SP, Bett AW, Horowitz K, Kurtz S (2014). Current status of Concentrator Photovoltaic (CPV) technology

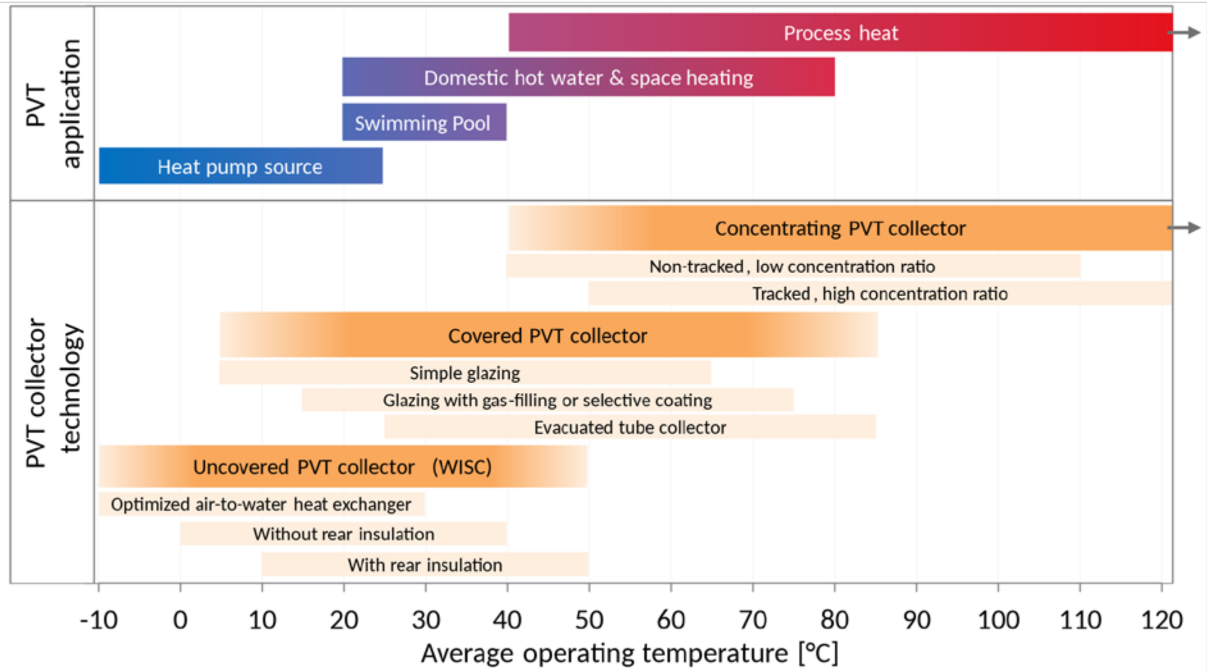

Figure 8-3: Map of PVT collector technologies and PVT applications per operating temperature.[14]

Depending on the type of heat transfer fluid, PVT collector technologies are suited for several applications:[15]

- PVT air collector: space heating systems, agricultural processes (e.g. drying crops);
- PVT liquid collector: Space heating (domestic, industrial), water heating systems, water distillation, space cooling, food processing systems.
- PVT technologies can bring a valuable contribution to the world's energy mix and should always be considered as an option for applications delivering renewable electricity, heat or cold.

8.4 Relevance in Building Competitions & Living Labs[16]

Due to its innovative character and its high energy efficiency, PVT collectors are a popular technological option in past building competition and living labs. Depending on the rules of the competition, more or less teams decide on the integration of PVT collectors into their building. The major advantage is seen in the high solar utilization efficiency, with the generation of heat and electricity from the same area.
The following table illustrates the utilization of PVT technologies in past Solar Decathlon Europe competitions. Depending on the year and corresponding guidelines, up to one third of all teams employ PVT collectors. Analyzing the PVT systems in more detail, shows that various different PVT designs (uncovered and covered, water and air PVT collectors), different thermal applications (direct heating of hot water, primary heat source for a heat pumps condenser, radiative cooling) and different methods for building integration (integration on a flat roof, on an inclined roof or into the façade). The collector area varies between 4 m² up to 70 m² (team DTU in 2012).

[14] Image by Manuel Lämmle - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=87526793

[15] Sathe TM, Dhoble AS. A review on recent advancements in photovoltaic thermal techniques. Renew Sustain Energy Rev 2017;76:645–72. doi:10.1016/j.rser.2017.03.075.

[16] Data of PVT systems in past building competitions are based on a separate analysis of usage of PVT collectors (personal communication with Karsten Voss). The underlying data can be found in the building competitions & living labs knowledge platform: https://building-competition.org/material/show/TOPA

Table 8-1: Statistics of PVT technologies in past Solar Decathlon Europe competitions

Year	Teams with PVT	Thermal application			Building integration		
		Direct heating	Heat pump	Radiative cooling	Flat roof	Inclined roof	Façade
2010	5/17	2	-	3	3	2	1
2012	6/18	4	3	3	4	2	-
2014	0/20	-	-	-	-	-	-
2019	3/10	3	1	1	1	1	1
	14 / 65	9	4	7	8	5	2

All teams combine PVT collectors with PV or solar collectors, while the PVT areas typically comprise a smaller fraction of the total solar active areas. The following figure shows a typical integration of PVT collectors (orange, eastern solar chimney) and combination with PV (yellow) and solar thermal collectors (orange).

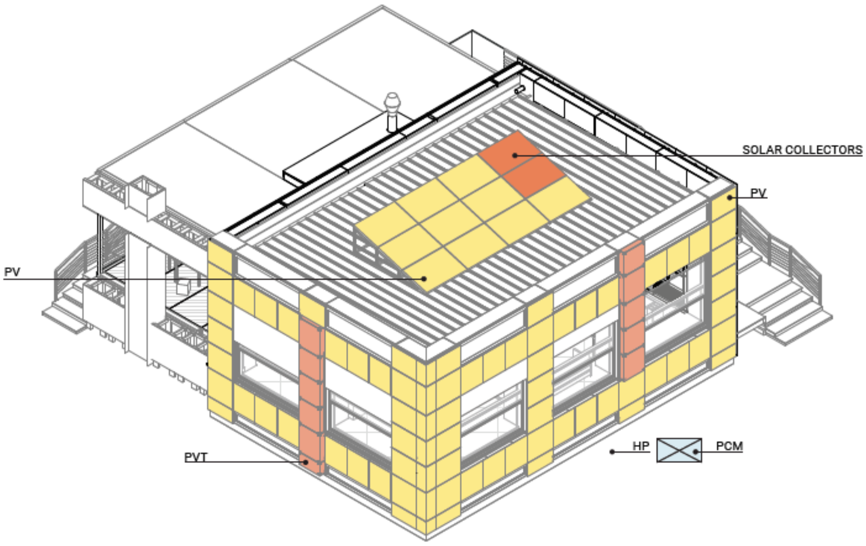

Figure 8-4: Building integration of PVT collectors on the eastern solar chimney and combination with PV and solar collectors by team TUD in 2019.[17]

To conclude, the combination of PV, solar thermal and PVT in building competition indicates that PVT collectors are considered an innovative, efficient hybrid technology with combined generation of heat and electricity and an optimized utilization of available areas of the building envelope.

8.5 Assessment of PVT Systems

8.5.1 Key performance indicators (KPIs)

A concise definition of Key Performance Indicators (KPIs) is essential to evaluate the performance of a technology, compare different components and system, or to assess the optimization potential. IEA SHC Task 60 – Report D1 defines the most relevant KPIs for PVT systems, which are mostly based on the KPIs of either solar thermal systems or PV systems. The essential Key performance indicators are summarized in the following table.

[17] TU Delft (2019), Project Manual, *TUD PM_D#7_2019-10-25.pdf*

Table 8-2: Key Performance Indicators for PVT systems, based on IEA SHC Task 60, report D2 – System Evaluation (Schubert et al., personal communication, to be published)

Category	KPI name	Symbol	Unit
Energy	Thermal and electrical solar yields per m²	q_{PVT}, e_{PVT},	kWh/m²
	Thermal and electrical utilisation ratios (yield/irradiation)	$\omega_{PVT,th}$, $\omega_{PVT,el}$	-
	Power-weighted collector temperature	$\vartheta_{char,power}$	°C
	Solar thermal fraction, solar electrical fraction	$f_{sol,th}$, $f_{sol,el}$	-
	Seasonal performance factor (for heat pump systems)	*SPF*	-
Financial	Specific investment cost per m²	*I*	€/m²
	Levelized cost of heat and electricity	*LCOE, LCOH*	€/kWh

These KPIs describe the characteristics of the PVT system and are therefore suitable parameters to compare the energetic and financial performance of different PVT systems, also in comparison with PV or solar thermal systems.

8.5.2 Simulation

The objective of simulating PVT systems is the energetic, economic and environmental assessment of PVT performance on collector and system level. Several commercial and non-commercial simulation tools are available, e.g. Polysun, TRNSYS, Modelica, ScenoCalc in Excel, etc.

PVT performance models link an electrical performance model of a PV system with a thermal performance model of solar thermal collector. In many approaches this is achieved by coupling the fluid temperatures of the thermal model with the cell temperature of the electrical model.

8.5.3 Monitoring

Monitoring PVT systems implies the measurement of the combined electrical and thermal performance of the PVT collectors in their system environment. Monitoring methods therefore combine the world of solar thermal systems with PV systems. Information on the monitoring of the individual systems can be found in the respective topical papers.

Post Processing of Results from Simulation & Monitoring

The basis for performance assessment from either simulation or monitoring, are in most cases time series for the simulated or measured variables. The post processing of data is typically done in three steps:

- filtering and aggregation of data
- calculation of performance indicators according to their definitions, typically for a full-year
- graphical visualization

Regarding the specifics of PVT collectors, the strong dependence of efficiency on the operating temperature has to be noted. Therefore, the solar yields should be strongly regarded within the system context, i.e. at which temperature levels solar heat and electricity is harnessed. The Power-weighted collector temperature $\square_{char,power}$ is a suitable KPI to describe the average operating temperature

8.6 Further Reading

The first three sections of this chapter summarize the following report and, in parts, use literal fragments without explicit citation:

[Laemmle 2020] Lämmle et al, IEA SHC Task 60, report D5 - Basic concepts of PVT collector technologies, applications and markets DOI: 10.18777/ieashc-task60-2020-0002, (not published yet). The mentioned report also formed the basis for updating the corresponding Wikipedia article: https://en.wikipedia.org/wiki/Photovoltaic_thermal_hybrid_solar_collector

[ieashc60 2020] IEA Task 60 “PVT Systems: Application of PVT Collectors and New Solutions in HVAC Systems”. Task Website: https://task60.iea-shc.org/

[Ramschak 2019] Ramschak et al IEA SHC Task 60, report A1 - Existing PVT systems and solution, 2019

[Schubert 2020] Schubert et al., IEA SHC Task 60, report D2 - System Evaluation (not published yet)

[Zenhausern 2017] Zenhäusern, Daniel, Evelyn Bamberger, and Aleksis Baggenstos. «PVT Wrap-Up: Energy Systems with Photovoltaic-Thermal Solar Collectors». 2017. Rapperswil, Switzerland: published by EnergieSchweiz. http://www.spf.ch/fileadmin/daten/publ/PVT_WrapUp_Final_EN.pdf

[Laemmle 2018] Lämmle, Manuel: Thermal management of PVT collectors - development and modelling of highly efficient PVT collectors with low-emissivity coatings and overheating protection. PhD thesis, Fraunhofer ISE (2018), INATECH Albert-Ludwigs-Universität Freiburg.
DOI: 10.6094/UNIFR/16446

9. Photovoltaic Systems

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9.1 General Relevance

Photovoltaics (PV) energy is a major actor in the development of renewable energy. PV panels directly produce electricity under the sun irradiation. They can be installed on small and big buildings as well as on ground or on solar trackers at utility scale. For buildings, they used to be installed on roofs to maximize energy production over the year. Most of the PV owners used to sell the produced electricity injected into the grid at an interesting rate to compensate the owner PV system cost. Therefore, the buildings were consuming and buying electricity from the local grid distributor. Together with building energy retrofit and low consumption buildings, net zero energy or net energy positive buildings can be achieved.

Nowadays, PV systems are more and more optimized for self-consumption because of the lower offered price for injected electricity. The PV owners can have an initial subsidy and they are encouraged to consume their own produced electricity. At a more global scale, this strategy implicitly promotes the production of local energy with self-consumption strategies, completing the traditional grid production fed by electricity produced by centralized power plants such as nuclear, fossil energies, hydraulic, or wind energy. Depending on the building typology, PV can supply a major part of the electrical consumption of the building, including appliances as well as building systems such as HVAC and DHW. Self-consumption can be increased using electrochemical batteries. Self-consumption (fraction of self-consumed solar energy related to the total generation) and self-sufficiency (degree of total consumption covered by solar) are different objectives and sensitive to the time resolution of the data. An autark building would require the installation of costly seasonal storage solutions such as hydrogen storage.

Thanks to the dramatic drop of prices and emerging Building Integrated PV (BIPV) products on the market, BIPV are now also installed on roof and facades with an acceptable return on investment. Furthermore, facade production represents a non-negligible potential of renewable and local energy production in the built environment in dense urban areas.

As part of the roof or facade, BIPV panels are not superposed to the passive building elements but replace them by active elements producing electrical energy. The BIPV elements can combine energy production with one or more other building envelope functions such as water sealing, thermal, insulation, solar protection or any other function. Thanks to its multi-functionality with associated material savings, the resulting embodied energy for the building is theoretically lowered. BIPV integration is generally more aesthetic thanks to the choice of customized dimensions, colors and texture, transparency, material composition (glass/glass frameless, glass backskin, etc.). The main drawbacks of BIPV is lower efficiency due to size customization or reduced panel efficiency (from 5% up to 50% in worst cases with some color panels). BIPV elements are generally more expensive as price per watt for the initial investment. However, this can be compensated by the fact that more active surface can be generally covered on the building thanks to size and aesthetic customization and the additional cost can be diluted by the saving of the building element itself. Moreover, the simultaneous installation of BIPV elements during the building construction or during energy retrofit of an existing building allows to drastically reduce the installation cost.

Any PV system is defined by installation parameters that will highly influence the annual energy production. The first set of parameters is linked with location latitude, longitude, and altitude. The closest local meteorological data must be considered for production calculation. Data are generally averaged values over several years, but can be time series as well. In addition, defining the short and the far field shading horizon can be very important in case of surrounding mountains, trees and other buildings. Then, the parameters linked with the integration of panels are set with orientation and inclination Integration types free, on roof or façade. A good back ventilation of panel with a cooling effect has a positive influence on the yearly production.

9.2 PV Technologies

The PV technologies can be divided in two main categories. The first one, representing about 90% of the market share [1] is based on Silicon absorbing material (c-Si) with the two dominant products mono crystalline silicon (mono-Si) and polycrystalline (multi-Si). The second one is based on thin film technologies with a high potential of reducing embodied energy such as amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIS/CIGS), Cadmium Telluride (CdTe) and organic PV cell (OPC). However, due their relative lower efficiency with a quantity of encapsulating material which remain unchanged, reducing the cost per watt as well as reaching the best environmental indicators such as GWP and CED per produced kWh over life time is very challenging. The thermal coefficient is lower, which is favorable in some cases with a higher specific energy production expressed in kWh per installed power kWp (kilowatt peak). Hetero-junction can be used to increase the efficiency, promising development are ongoing such as Perovskyte and amorphous silicon on the silicon absorber.
Output power is given under standard conditions STC defined by sun spectra AM1.5 and direct sun irradiation 1000W/m^2 @ 20°C. Electrical characteristics IV curves with V_{oc}, I_{sc} resulting from cells in series and parallel also given at different illumination. The panel efficiency strongly depends on the active area with cells, the cell technology and the transparency of the front glass. The yearly production is also influenced by the temperature coefficient and the NOCT, both has to be the lowest as possible.
DC/AC-Power Conversion
PV-Systems generate DC power at various voltage levels. Maximum power from the IV curve of panels is extracted by using a Maximum Power Point Tracker (MPPT). Depending of the consumer coupled the PV panels producer, the MPPT is integrated to DC/DC converters or in the DC/AC inverters. The consumer can be AC grid, AC loads of the building or a DC or AC electrochemical battery. The panels are generally connected in series before the conversion up to the maximum voltage and power of the converters. Panels in series are also limited to a maximum for security, in general 1000V as a standard. Alternatively, individual panels can coupled with micro-inverters (DC/AC) or power optimizer (DC/DC) with one MPPT per panel. This solution has the advantaged to overcome the problem of panel electrical mismatch due to fabrication differences or shadowing effects on a series of panel connected together, yearly production can therefore be higher.

9.3 Relevance in Building Competitions & Living Labs

Sun powered houses are promoted by the Solar Decathlon competition (SD), and all PV technologies available on the market are to be represented. Depending on the rules of the competition, the maximum installed power is limited, to promote low consumption buildings. However, the limitation of installed power can be an obstacle to the installation of PV on façade because such installations cover larger surfaces with lower energy yield.
New PV technologies and non-certified products can be presented at the competition but with some limitations depending on the competition rules. Unless existing certification of the PV products, the voltage of the PV system can be limited for prototype. Case to case negotiations with SD organizers can be done for PV systems prototypes and proofs of performed reliability and security test must be shown. Developing prototypes in the frame work of the competition is interesting to promote emerging products, in particular in the BIPV market and high efficiency panels. PV coupled with direct heat energy generation are also of interest in SD competitions. This can be achieved by recovering heated air behind panels, or coupling Solar Thermal collectors (ST) with a circulating water. The last one is named as hybrids PVT panels. PVT panels produce heat as about 1/3 of standard ST panels and a slight improvement of the electrical energy yield is expected because of the water cooling effect of the PV cells thanks to circulating water.

Typically, the PV output is considered in SD as part of the energy balance contest and associated sub-contests (100 to 120 points). No contest for the PV system performance itself exists up to now as all sub-contests address the balancing of generation and consumption combined.

9.4 Certification, Security, Reliability

PV panels in series represent an electrocution hazard risk in case on defect of panel electrical insulation. The panel insulation must be guaranteed over the entire lifetime of the panels that is greater than 20 years. The certifications of PV product, IEC 61215 for multi-Si and 61646 for thin-film (a-Si, CIGS, CdTe), simulate ageing in outdoor conditions by doing test such as damp heat, humidity freeze and thermal cycling. Aesthetic appearance, panel performance and electrical insulation is checked after the tests. The IEC compliancy also includes mechanical and fire resistance tests. The tests give only an idea of the panel reliability which will depends on specific climate and integration conditions. Manufacturer generally offer panel warranty of 10 years for components defect and 80% of initial efficiency after 20 years in operating conditions. In the case of BIPV, typically in facade, the panel must be also complaint with the buildings rules.
Minimal requirements are necessary when installing panel prototype and pilot projects. If IEC certification cannot be provided, equivalent laboratory reliability tests must be shown and the components must be certified individually. The risk to install uncertified product is dramatic loss of PV system performance after few years, a change in the visible appearance as well as an electrocution
In case of R&D prototype, the voltage of the panel should be limited to 50V and must not be connected in series to limit the high risk of electrocution.

9.5 Environmental Impact

The 'cradle to cradle' life cycle of PV should be considered, from the row material of PV panels and balance of system (BOS: module supports, cabling, and power conditioning) until disposal and recycling of the installation. The environment indicator CED (primary energy use), CED_{nr} (no renewable energy use in MJ) and GWP (Gas Warming Potential in $kgCO2_{eq}$) can be expressed per m^2, or per kW_p by taking into account the panel efficiency. The embodied energy can be obtained from data base such as ecoinvent (see Table 9-1) as well as study report [3].

Table 9-1: Environmental indicator of a 3kWp installation in Switzerland per kWp, 2015

Slanted-roof installation, Laminated, Integrated.	*GWP* [$kgCO_{2eq}$/kWp]	*CED* [MJ_{eq}/kWp] / [kWh/kWp]	*CED_{nr}* [MJ_{eq}/kWp] / [kWh/kWp]
Multi-Si, eta_{STC}=15.1%	1847	32'070 / 8'908)	27'302/ 7'584
CdTe , 73_{STC}=13.5%	1350	21'953 / 6'098	20'278 / 5'633

The impact factors of (BI)PV per kWh or produced energy is finally evaluated on the basis of the embodied energies and the predictable energy generation over their entire lifetime of maximum 30 years. Therefore, for a given technology, the environmental indicators will be reduced by installation with high yearly production strongly influenced by installation parameters. Typical energy payback time lower than two years can be achieved at Mid European conditions with photovoltaics (standard installations), and it can be demonstrated that installing PV on building reduces the carbon footprint [4]. Note that coupling PV with storage systems to increase self-consumption has the consequence to increase the total embodied energy. Therefore self-consumption strategies such as multi-oriented façade (see Figure 9-1), time shifting of loads with suitable algorithms and coupling PV with building systems should be promoted.

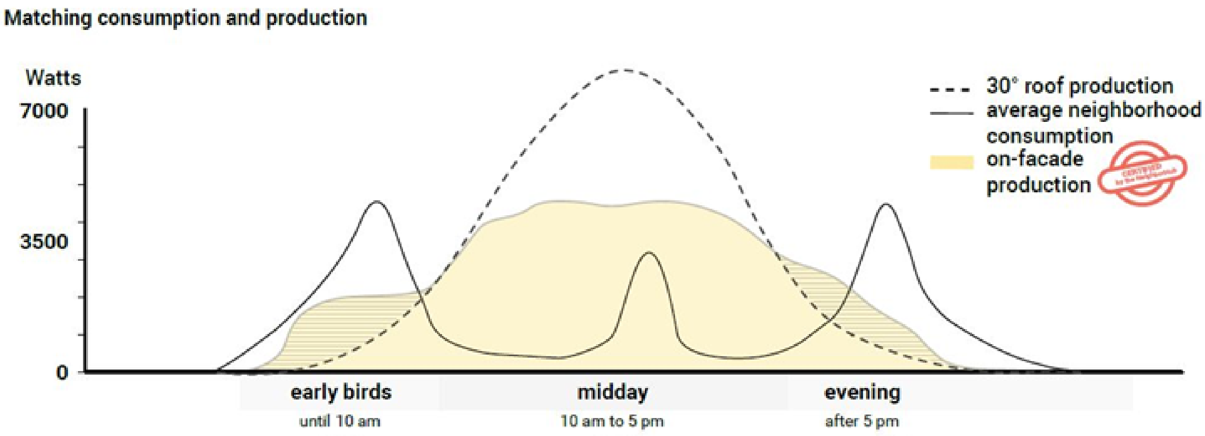

Figure 9-1: Strategy of a multi-oriented south, west and east facades to optimize self-consumption. Source: Swiss Living challenge [5], DOE US solar decathlon 2017 Denver Colorado.

9.6 Simulation & monitoring

Commercial software such as PVSyst (CH) or Polysun (CH) and general building planning such as DesignBuilder (US) can calculate energy production on a yearly, monthly and hourly basis. The two last software are able to calculate the coupling with building systems, which is a strong advantage when optimizing the self-consumption. These tools are used for the planning phase of the building before the installation; it also includes guide wizards for the dimensioning of the PV systems.
After installation, the PV system under operation can be monitored with details using the Inverters web portals or solar Datalogger such as meteocontrol or solarlog commercial products. Simple energy counters can be used alternatively without inverter's detailed measurements. The comparison between the yearly production and the production simulations of planning phase is the minimum, check but real time comparison can be done if weather historical data are available.

9.7 Post Processing of Results from Simulation & Monitoring

The performance of the PV system is given by the performance ratio (*PR*, see norm IEC EN 612724) of system as follows:

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

Unlike specific energy production indicator, expressed in (kWh/kWp/year), *PR* gives the performance of the installation independently of the orientation, inclination of the panel and weather conditions. *PR* values ranges from 0.7 to 0.9 with good system quality. PR includes all losses: inverter, temperature, DC cables, AC cables, panel mismatch, shadings, losses at weak radiation, losses due to dust, snow, ageing etc. [2].
In Figure 9-2, simulation and monitoring results from a 435 kW_p installation near Fribourg are graphically shown. The installation has 361 kW_p on roof (5° inclination) and 74 kW_p on south façade. The *PR* of the installation is 0.78.
For a detailed PV system analysis and diagnostic, the hourly simulations can be compared with the real measured production : lower efficiency at low illumination can be caused by inverter threshold or cracks in panels, or lower efficiency at high illumination can be caused by serial resistance in panels or inverter power clipping. Final diagnostic will be provided by checking the hardware (visually, with the help of infrared camera for hot spots…) and measuring electrical characteristics (V_{oc}, I_{sc}, IV curves) of panels and strings directly on the installation site.

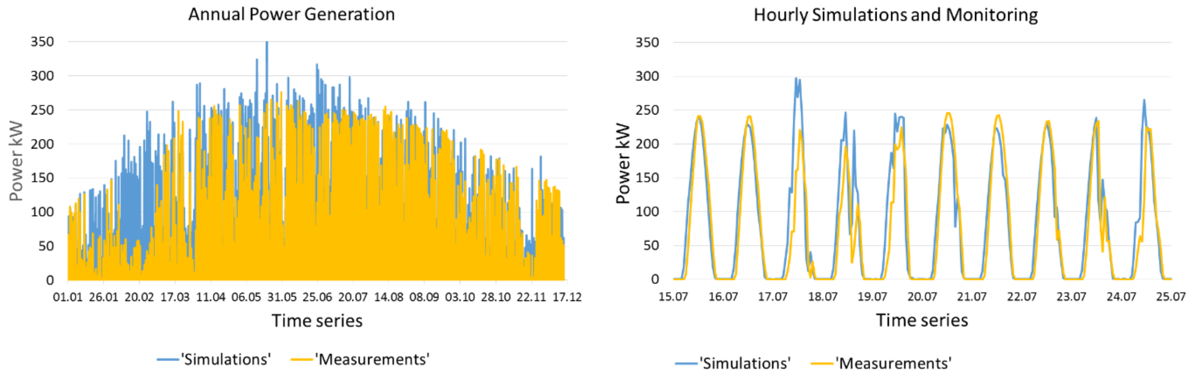

Figure 9-2: (Left) Annual Power Generation 2013 of a 435 kWp Solar Power Plant in Western Switzerland. (Right) Hourly simulations and monitoring in clear sky conditions during summer.

9.8 Further Reading

[1] Fraunhofer Institute for Solar Energy Systems ISE, ⟨http://www.ise.fraunhofer. de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer- sprache.pdf⟩; 2019.

[2] Renewable and Efficient Electric Power Systems, De Gilbert M. Masters

[3] IEA International Energy Agency, " Life cycle Assessment of Future Photovoltaic Electricity Production form Residential-scale Systems Operated in Europe', Report IEA-PVPS T12-05:2015, IEA-PVPS Task 12, Subtask 2.0, March 2015, R Frischnecht, René Itten, F Wyss

[4] D. Vuarnoz, S. Cozza, T. Jusselme, G. Magnin, T. Schafer, P. Couty, E.L. Niederhauser, « Integrating hourly life-cycle energy and carbon emissions of energy supply in buildings », Sustainable Cities and Society, Volume 43, November 2018, Pages 305-316,

[5] Positive energy building with PV facade production and electrical storage designed by the Swiss team for the U.S. Department of Energy Solar Decathlon competition 2017 Denver, P. Couty , M.J. Lalou, P. Cuony, S. Cotture, V. Saade, Colorado, Conference CISBAT 2017, Energy Procedia 122 (2017), 919–92

10. BATTERY STORAGE SYSTEMS FOR BUILDING APPLICATIONS

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10.1 General Relevance

Ambitious goals in term of renewable energy penetration and C02 emission reduction have been set world-wide and at a country level [1], [2]. Within this context, as depicted in several references [1-6], electricity storage will play a crucial role in enabling next phase of the energy transition and in decarbonising key segments of the energy market. In the incoming years, battery energy storage systems BESS can be grouped in three main usage-categories: (i) stationary, (ii) electric vehicles (EVs) connected to building (the so-called vehicle to building V2B) and iii) second-life systems. The first ones are, and they will be, more and more deployed in (i) buildings for increasing energy renewable self-consumption and compensating daily volatility of renewable energies and in (ii) power grid to provide ancillary services (frequency control, peak shaving, etc.). Batteries in EVs will also be deployed to provide ancillary services to the grid (V2G) or to building (V2B). Second-life batteries, coming from aged EVs, could be deployed with reduced performances for grid and building applications from 2023 (the forecasted date for large amount of aged cells from EVs).
Various battery technologies are used for both stationary and EV applications [7-8]. The lead-acid (PbA) and lithium-ion (Li-ion) are dominating the market but other technologies are co-existing such as nickel-cadmium, nickel-metal hybride and nickel-iron (NiCd/NiMeH/Ni-Fe), sodium−sulfur (NaS), sodium-nickel-chloride (NaNiCl), redox-flow batteries vanadium- (V-Redox) and zinc –Bromine (ZnBr). The main battery characteristics are listed in Table 10-1. The cycle life is the number of charge/recharge cycles that the battery can support before its capacity falls under 80% of the initial value. The manufacturers also give the value in percentage of the maximum depth of discharge (DOD), where DOD is the complement of the state of charge of the battery (SOC). Typically, Li-ion have maximum DOD ~80%-90%, and PbA ~50%. Note that the larger the DOD every cycle, the smaller the available cycle times will be.
For the home storage application, the lead-acid and lithium-ion technologies coupled with PV [10] are commonly used. PbA batteries represent one of the oldest and most developed battery technologies. There are many existing installations which have been in operation for up to 20 years. Their biggest advantage is the low cost compared to other storage systems, demonstrated recyclability [11], while their limited lifetime with a limited number of cycles is the biggest disadvantage. Improved version of flooded lead-acid (FLA) are sealed lead acid valve-regulated lead-acid VRLA batteries such GEL and absorbed glass mat AGM, GEL having lower charging power. They are recommended to be used with PV because of their low maintenance and extended depth of charge resilience. Ongoing R&D is focused on extending lifetime and improving performance both in terms of charge acceptance and in their ability to operate partial state of charge applications. Advanced lead-carbon batteries as well as lead crystal batteries are claimed to have better performance and still good recyclability.

Table 10-1: Main characteristics and performance of various battery technologies, data source 2011 [8]

Technology	Energy efficiency (%)	Self discharge (days/%[18])	Gravimetric energy density (Wh/kg)	Volumetric energy density (Wh/L)	Cycle life (cycles)	Float life (years)	Working temperature (°C)
Pb-acid	70-90	3-15	20-50	50-80	500-2000 4500*	5-15	10-45
NiCd	60-87	3	50-80	40-100	1500-3000	-	-40-60
Li-ion	85-100	3-15	60-200	200-400	1000-10'000	5-15	-
NaS	75-92	0-0.05	110-240	150-250	>2500	10-15	270-350
NaNiCl	70-90	0.06	100-200	150-180	>2500	10-14	270-350
VaRedox	60-85	Lot of days	10-30	15-33	10'000-13'000	10-15	5-45

Li-ion has become the most important storage technology in the area of portable and mobile applications (e.g. laptop, cell phone, electric bicycle, and electric car) within a few years. In stationary applications, Li-ion can be found in variable size from few kWh of capacity up to hundreds of MWh. Their advantages are high density energy, good round trip efficiency (>85%), fast response in milliseconds, low self-discharge rate, high power charge and discharge, and high cycle life. Significant resources will continue to be spent on improving the performance, cost, systems integration, production processes and safety [9]. Demonstrating recyclability and reducing operating temperature are also required. Li-ion batteries decline in the following sub-technologies: lithium polymer batteries (LiPo) with highest energy density, lithium iron phosphate (LFP), li-ion manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium ion titanate (LTO). The commonest chemistries for residential BESS are NMC- graphite or iron-phosphate, since they have a quite important energy density (120-160 Wh/kg) and long lifecycle (up to 10000 full equivalent cycles). LTO have a very high number of cycles 15.000-20.000. Compared with PbA, Li-ion batteries cost more up front, but the extra efficiency means you can potentially spend less per kilowatt-hour of capacity over the lifespan of the battery. Moreover, Li-ion lasts longer and have faster charge rate and can be put through deeper cycles. The energy density has increase a lot last decade, passing from 60-70 Wh/kg up to 140/200 Wh/Kg for modern NCM graphite li-ion cells [12].

10.2 DC/AC-Power conversion

BESS are composed of cells which are charged and discharged at DC current. The maximum charge and discharge rate depends on the batteries size and cell technology. To guaranty lifetime and security, a battery management system (BMS) is embedded into the Li-ion systems to monitor cells voltage, temperature as well as to control the maximum allowed charge and discharge current. There is generally no BMS for lead-acid batteries which are totally passive. As the battery is DC and since the building is connected to an AC grid with a majority of AC consumers, a reversible DC/AC converter, called charger-inverter is needed. The charger convert AC to DC, and the inverter DC to AC. For Li-ion, this charger inverter is talking via a communication link with BMS which define the maximum charge and discharge DC current. Some BESS manufacturer also propose to integrate the charger inverter within the BESS. To store and restore electrical energy, the BESS is coupled to the AC grid and the PV system in different manners. The PV system can

[18] Self discharge is expressed here in days/% and means the number of days it takes for a 1% loss

be coupled in DC to the BESS with the help of a DC/DC converter. The alternative is to connect the PV system to BESS after solar inverter (AC coupling).
Finally, the typology of the Grid - BESS - PV system - Consumers must be defined with three main possibilities: (i) consumers and loads must be fully secured, (ii) few loads must be secured, and (iii) no load must be secured by the BESS that only restore energy with a permanent connection to the grid. The two last cases correspond to the context of a house connected to the grid in a built environment where the grid is supposed more reliable than the BESS. In this case, the PV system in AC is also connected to the grid side with no limitation of PV power. As most of loads (except the secured ones) are also connected to the grid side as well, the power of the charger inverter is only dimensioned by the power of the BESS and not the loads.

10.3 Relevance in Building Competitions & Living Labs

In buildings, energy storage combined with intermittent renewable systems is a common solution for increasing the use of low-carbon energy produced on-site. The use of electric storage batteries was already part of the SD US 2002 competition. Until 2007, SD houses were not connected to the grid and the installation of batteries was mandatory. In SD Europe, batteries have been authorized since 2010, with limited power and capacity. As the buildings are connected to the grid, installing large electrical storage capacities to make the house autonomous no longer made sense. The average battery size has therefore decreased from 85 kWh (SD US 2007) to 13 kWh (SD US 2017) and 5 kWh (SD EU 2014). By limiting storage capacity, limiting the PV production and minimizing the perceived energy of the grid, the SD rules force candidates to reduce their consumption as much as possible and implement advanced control strategies. In European SD competitions, the criteria for evaluating the energy contest and the score assigned to SD houses have evolved over the years. The contest "*Positive Electrical Balance*" was worth 75 points (out of a maximum of 120 points concerning energy) in 2010 and more than 25 points in 2014. Since SD EU 2014, rules have been in place to evaluate the interaction between SD houses and the grid. They take into account the ability to avoid power peaks at the building level but also the ability of the building to reduce grid power peaks. Apart from electrical characteristics and performance of BESS, the working temperature of BESS as well as the battery cells technology are of primary importance for SD. If lead-acid have lower capacity at low temperature, battery management system of Li-ion automatically switch-off the battery at low temperature and low cell voltage. Other bigger BESS such as Tesla Powerpack have their own battery temperature regulation system with heating and cooling. This regulation consumes energy in addition to the intrinsic self-discharge rate of the cells and the charger inverter consumption. It is therefore important that the battery have sufficient cycle to maintain by itself at the right temperature (23°C +/- 4°C optimum for Li-ion NMC) thanks to the charge and discharge current during cycles. Also, proper ventilation, natural or mechanical ventilation is mandatory if BESS electrolyte can generate toxic and inflammable gas. Finally, since sustainability is a criterion for SD, the LCA of BESS with the chosen technology must be carried out considering both embodied energy and delivered energy during the whole BESS cycle life.

10.4 Performance Indicators for BESS

The performances of a BESS is related with the technology characteristics listed in Table 10-1 as well as its sizing and integration. In particular, the BESS is defined by its capacity (strictly related to the energy that could be stored in), the equivalent series resistance (strictly related to the power that could be deployed with). The regulation strategy and dimensioning is decisive for qualifying the performance of the installation. Several strategies can be identified. An **energy strategy** aims to reduce dependence on the grid and thus increase the building's self-consumption ratio (SCR) and self-sufficiency ratio (SSR). An **economic strategy** considers variations in the price of perceived energy from the grid, increases the economic profitability of the installation and reduces payback time. SCR and SSR indicators are calculated with the help of the following equations, where E represent energy yearly flows:

$$SCR: \ Self - Consumption\ Ratio = \frac{E_{self-consumed}}{E_{self-produced}} = \frac{E_{consumed} - E_{fromgrid}}{E_{consumed} - E_{fromgrid} + E_{togrid}}$$

$$SSR: \ Self - Sufficiency\ Ratio = \frac{E_{self-consumed}}{E_{consumed}} = \ 1 - \frac{E_{fromgrid}}{E_{consumed}}$$

An **ecological strategy** takes into account the ecological impact of the installation. Indeed, the installation must lower the carbon footprint of the building by limiting the use of fossil energy delivered by the grid that is not constant and depends on its mix source (fossil, wind, hydro, nuclear, etc.) [13]. Assessment (LCA) should be computed in order to have an overall vision of the BESS impact [11][14-15]. It is worth noting that a BESS having a reduced ageing will live for longer time, and consequently it will store more renewable energy Therefore, the environmental indicator gas warming potential GWP in kg eq CO2 and cumulative energy demand in MJ must be expressed per unit energy total delivered energy in MWh. The total delivered energy will depend on the BESS size and cycle life.

There are other criteria defined by the SD rules such as smoothing the power peaks consumed by the SD house or help the grid to compensate for overloads. These strategies can be combined to meet several objectives. The regulatory choices and the importance given to each of these strategies will be influenced by the competition rules and the scoring criteria.

10.5 Basic BESS Sizing

The main important physical parameters to consider when dimensioning BESS are the following: capacity, maximum number of cycles, maximum allowed depth of charge to avoid irreversible damage, maximum charge and discharge rate. The prerequisite to design a storage system for stationary application is to know the PV production and the electrical consumption. As a rule of thumb the size of the BESS should not exceed 30-40% of the overall average daily consumption, or should be able to bring an autonomy of 4h-8h duration. The nominal power of the inverter to be connected with the BESS should not exceed 60% of the PV peak power production.

A family house located in Neuchatel (CH) and designed for four persons is taken a case study. The house has an energy reference area of 140 square meters. A passive house standard design would lead to a yearly electrical consumption is 4200 kWh including 2800 kWh for the appliances. A design that complies with current minimal standards in Switzerland would lead to a yearly consumption of about 7400 kWh with 4200 kWh for appliances. With a target of a minimum PV coverage ratio of 60% and energy yield of 130 kWh/m2, the required PV surface is 34 m2. Considering an average daily energy consumption of 20 kWh, the capacity of a battery corresponding to 30-40% of this energy would be between 6 and 8 kWh.

For better insights about BESS sizing before performing simulations, a web-based design tool can be found in [16] with an illustration Figure 10-1. This simple digital tool estimates the self-sufficiency and self-consumption rates as well as battery use. Taking again the example of a house with 4.4 kWp installed power and 7400 kWh energy consumption, variable battery capacities 4, 6 and 8 kWh lead to variable self-consumption (70%, 78% and 85%) and self-sufficiency (40%, 44% and 47%). However, this tool has strong limitations because it is not possible to model the technical installations and equipment of a specific building.

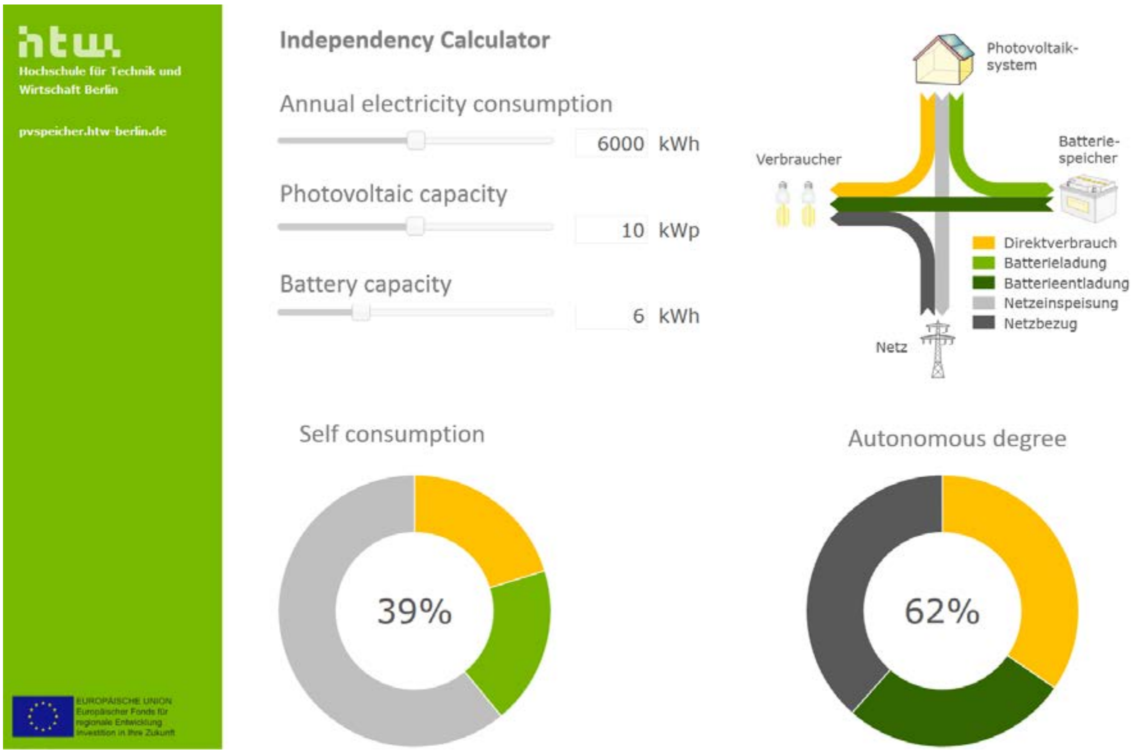

Figure 10-1: Screenshot of a digital tool for BESS sizing [16].

10.6 Building systems Simulations with PV and batteries

The behavior of a BESS coupled with building systems and PV can be simulated [17] with the help of building simulation software such as Polysun [18]. As an example, a two-floor house in Neuchâtel is considered with the following characteristics:

- Energy reference area: 140 m2
- Yearly heating demand: 30 kWh/m2
- Domestic hot water DHW consumption: 5.8 kWh/day (200 l@ 50°C)
- Residential electrical consumption profile 3500 kWh/year.

To optimize the self-consumption, the 10 kW heat pump is fed and driven in priority by the PV roof top production, see Figure 10-2.

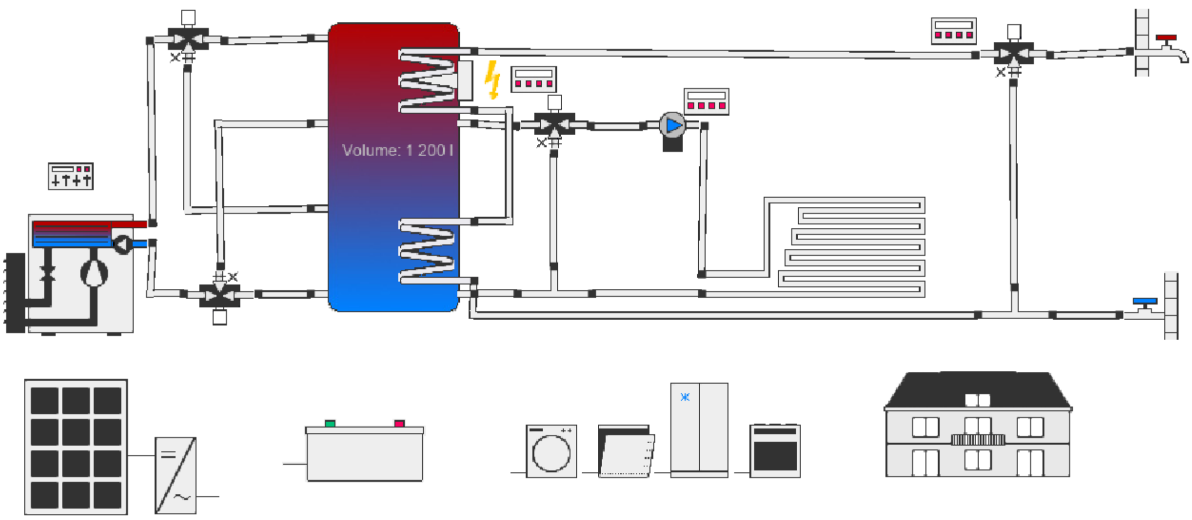

Figure 10-2 : Building system simulations with variable PV coverage and battery capacity for a low consumption building 140 m2 equipped with a PV driven heat pump for heating and domestic hot water, Polysun model 56c [18]

A first set of simulation is presented in table 2: variable PV coverage with installed power 4, 5.6, 8.1 and 11.8 kWp (Poly-Si @ 45° South), as well as variable battery storage capacities 0, 4 and 8 kWh (Lithium-Fe-P Sonnen, 10’000 cycles AC coupling). Comparing the three first columns, the self-consumption already go from zero with No PV to 42% with PV without BESS. Then, adding the BESS 4 kWh brings an additional self-consumption of 27% (42% to 69%). Increasing PV and BESS size, self-consumption reaches a maximum of 78.4% for the median coverage 80% (5.6 kWp) and BESS 8 kWp, but deceases when PV coverage is further increased because un-consumed energy is injected into the grid. Note that, the introduction of an electrical vehicle would dramatically increase both the electrical consumption of the house and the self-consumption for the large PV installation as well. Considering the self-sufficiency ratio, an increasing of the PV coverage from 59% (4 kWp) to 158% (11.8 kWp) leads to a maximum value of 59% (BESS 8 kWh). Nevertheless, self-sufficiency of 45% is already obtained with 5.6 kWp of PV and a BESS of 4 kWh.
To determine the **optimum BESS size maximizing self-consumption**, a fix PV coverage of 80% of the electricity consumption is considered (5.6 kWp) and the BESS size varies from zero to 32 kWh (see table 3). The self-consumption ratio rapidly reaches a maximum value of ~80% for BESS 10-12 kWh. A bigger BESS capacity may be chosen in order to guarantee the self-consumption level over years. This would compensate the loss of battery capacity per year in % which depends on the number of cycles and deep cycles. Increasing BESS size, self-sufficiency increases up to 47.5% with the largest battery 32 kWh, which is lower than the PV coverage ratio. From the **environmental** point of view, since the battery has embodied energy, the battery size must be minimized.

Table 10-2: Variable PV coverage and BESS capacity in kWh.

Variable PV size kWp **Variable BESS size kWh**	**NO PV** **BESS 0**	**PV 4** **BESS 0**	**PV 4** **BESS 4**	**PV 5.6** **BESS 4**	**PV 5.6** **BESS 8**	**PV 8.1** **BESS 4**	**PV 8.1** **BESS 8**	**PV 11.8** **BESS 4**	**PV 11.8** **BESS 8**
PV coverage [%]	0	59	58	80	80	118	118	157	158
PV production [kWh]	0	4080	4080	5767	5767	8698	8698	11795	11795
Energy from grid[kWh]	6883	5233	4591	4004	3797	3596	3366	3340	3072
Energy to grid [kWh]	0	2379	1070	1872	1249	4223	3570	6963	6265
Elect Consump. [kWh]	6883	6935	7007	7226	7213	7396	7383	7498	7484
Self-Consumption[kWh]	0	1702 (42%)	3011 (69%)	3896 (67.6%)	4519 (78.4%)	4476 (51.5%)	5128 (59%)	4833 (41%)	5531 (46.9%)
Self-Sufficiency [%]	0	25	34	45	47	51	54	55	59
Battery cycles [-]	0	0	665	883	882	843	845	812	813
Bat. loss capacity [%/y]	0	0	2	2.6	3.9	3.3	4.3	3.5	4.2

Table 10-3: PV coverage 80% PV 5.6 kWp, Variable BESS capacity in kWh

PV 5.6 kWp **Prod. 5782 kWh/year** **Variable BES size kWh**	**BESS 0**	**BESS 4**	**BESS 6**	**BESS 8**	**BESS 10**	**BESS 12**	**BESS 14**	**BESS 16**	**BESS 32** **2x16**
Energy from grid [kWh]	4808	3996	3838	3794	3779	3826	3842	3866	3786
Energy to grid [kWh]	3424	1881	1489	1262	1092	1114	1076	1027	893
Elect Consump [kWh]	7166	7226	7216	7213	7213	7212	7211	7211	7208
Self-Consump [kWh]	2358 (40.8%)	3902 (67.5%)	4293 (74.2%)	4520 (78.2%)	4690 (81.1%)	4668 (80.7%)	4707 (81.4%)	4756 (82.3%)	4890 (84.6%)
Self-Sufficiency [%]	32.9	44.7	46.8	47.4	47.6	46.9	46.7	46.4	47.5
Battery cycles [-]	0	906	918	997	883	874	851	839	828
Bat. loss capacity[%/y]	0	3	4.4	4.1	3.3	2.6	2.2	1.8	1

10.7 BESS economic analysis

We will consider the case study described above with a retail tariff equal to CHF 0.22 per kWh and feed-in equal to CHF 0.085 per kWh. From a user perspective, the revenue is equal to the difference between the cost of a grid-connected solar home battery system and the cost of grid as a zero-investment generator producing at the retail price. Accordingly, the energy fed to the grid should also be taken into account as a negative cost as follows:

$$Revenue = (E_{consumed} - E_{fromgrid}) \times Tariff_{retail} + E_{togrid} \times Tariff_{feedin}$$

For the example above, considering a 5.6 kWp PV installation and without any BESS, the yearly revenue would be CHF 810.-. Adding an 8 kWh BESS would increase the revenue only by CHF 50.- (total of CHF 860.-). This shows that an amortization of a BESS in such case would be almost impossible. However, the price of BESS has already dramatically decreased the last decades and second-life battery systems are emerging and might provide interesting economic models.
An **economic optimum** could be calculated by comparing the yearly amortization of the initial investment for PV plus BESS with the revenue as defined above.

10.8 Monitoring and control, Energy Management Systems

To prevent any unsafe operating conditions, industrial BESS are already equipped with Battery Management Systems (BMS) that monitors the state of charge of the BESS, cell voltage and current as well as temperatures. Typically for lithium-ion battery, BMS must communicates with the charger inverter to give the maximum charge and discharge current which depends on cell technology, cell's temperature and state of charge.
To be able to regulate the installation according to the desired strategies (see section *Performance indicators for BESS applications*), the building must be equipped with electricity meters to measure (i) PV production, (ii) the energy delivered by the grid and that provided by the grid, (iii) the consumption of the SD house and (iv) the energy stored in the battery. Meters dedicated to specific devices or services (e.g. heating system, EV, domestic appliances etc.) can also be considered. These allow detailing the building's consumption, to understand the users' habits and to use possible patterns for predictive purposes for BESS regulation. Energy management system integrating specific algorithms can be implemented to drive the BESS with charge and discharge current, possibly some load time shifting can be done (heat pump, washing machine …). For basic self-consumption strategies, the PV inverter manufacturer generally offer self-consumption solutions with the monitoring and control of the PV production, consumption and battery monitoring (SMA, Kostal…).

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11. Energy flexible buildings

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11.1 General relevance

The growing share of renewable energies in the distribution network associated with the energy turnaround is increasingly leading to new challenges. Due to the fact that the CO2 intensity of the grid electricity varies over time, it is advantageous to reduce emissions by adjusting the electricity consumption of a building accordingly. Unsteady feed-in behavior during the course of the day, the expansion of electromobility, and the steadily increasing number of power-intensive consumers can lead to a drop in grid voltage and to thermal overloads of equipment such as cables or transformers, see Figure 11-1 [Hermanns, 2020] [Möller, 2019] [Uhlemeyer, 2019]. In order to meet these challenges, more flexible and controllable loads will be required in the future, which is why building-network interaction is becoming increasingly relevant.

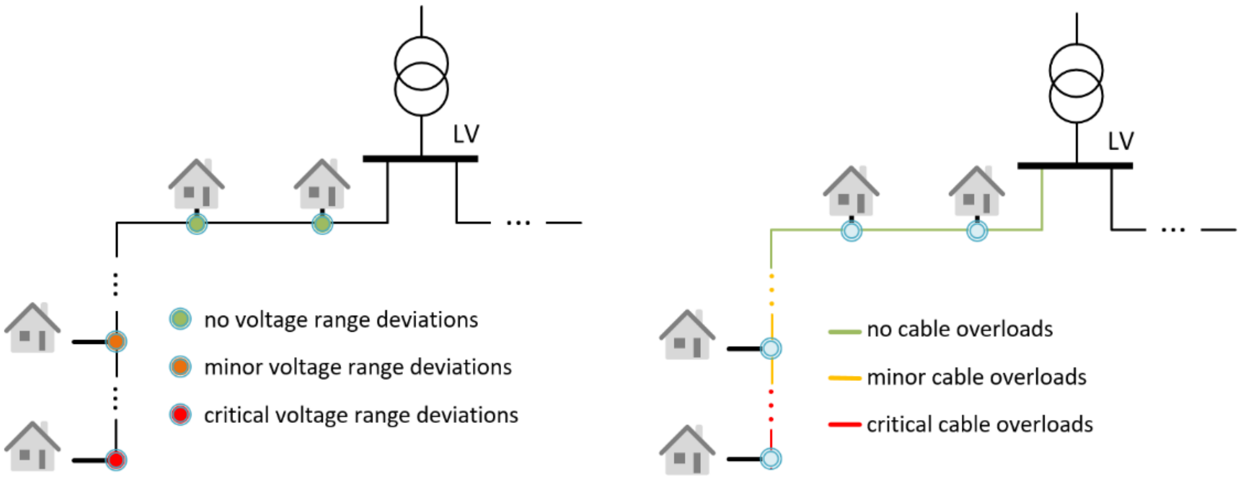

Figure 11-1 : Voltage band violation and equipment overload in the low-voltage grid, Source: University of Wuppertal, David Cano-Tirado

In order to limit the negative factors mentioned above, a paradigm shift in consumption behavior must be implemented. Where production has followed consumption in the past, consumption must in future follow production in suitable areas. In order to meet this demand, intelligent load management systems are required which can influence the operation of appliances, e-charging points and the supply technology of buildings.

Battery storage systems in combination with a photovoltaic system increase own consumption and the degree of self-sufficiency, which relieves the distribution network and means that fewer cable lines have to be reinforced. Battery storage systems are also suitable for attenuating power peaks in the consumption profile for the distribution network by buffering part of the required energy quantity. Thermal storage in the provision of heat and cold works in a similar way. In almost all types of energy storage, however, losses have to be taken into account, which are to be counterbalanced by the advantage of flexibilization. In addition, in hybrid supply systems, energy sources can be changed depending on the grid requirements (fuel switching).

Buildings are suitable for coupling the electricity and heat sectors. If there are thermal storage facilities, cogeneration plants can be used in winter to prevent a drop in the grid voltage by feeding more electricity into the distribution grid through increased operation or by covering a larger proportion of the building's own consumption. Among other things, separate a water storage tank or the activation of the thermal building mass [Leopkey, 2016]. On the other hand, electric heat pumps can be used to reduce short-term increases in voltage bands [Hobert, 2020]. In all these cases, a communication infrastructure is required, e.g. via the building control system, in which information about the power grid is incorporated into the building operation.

The electrification of individual traffic represents a great opportunity for the sensible intermediate storage of electrical energy. Instead of producing additional batteries and installing them in the home, the rechargeable batteries already installed in cars can be used. In combination with a charge management system, the distribution network can be supported by means of peak shaving and energy costs can be reduced by increasing the consumption of the vehicle and taking advantage of low tariff times [Hemmati, 2019].

The network-related use of flexibility options requires new operating models and compensation mechanisms. One option to overcome short-term grid bottlenecks are local dynamic market models. In these, a network bottleneck is forecast, the amount of flexibility required to remedy it is determined and then an application is put out to tender on a non-discriminatory market platform. In this way, the contract is always awarded to the cheapest provider [R. Faia 2019]. Joint ventures are conceivable as an alternative to the market model. In these joint ventures, distribution system operators participate in investments in third-party systems or equipment on the condition that these are used for grid-related purposes in addition to daily operations.

In the planning phase of buildings or prior to extensive renovations, relevant directives and laws should be examined for opportunities. For example, the retrofitting of charging infrastructure, as required by EU Directive 2018/844, for every parking space in residential buildings (from 10 parking spaces), results in additional costs and special requirements for the performance of the house connection. This offers the opportunity to cover costs by aggregating and marketing charging capacity on the flexibility markets described above.

11.2 Relevance in competitions and living labs

In the Solar Decathlon Europe 2010 and 2012, the main focus was on the energy balance of the buildings [SDE10] [SDE12]. Additionally relevant assessment indices in this context are the degree of consumption and the degree of self-sufficiency, which are calculated according to formula (1) and (2). The first-mentioned index describes I_{SC} how much of the self-generated electricity is used directly or indirectly, through intermediate storage. The degree of self-sufficiency I_{SC}, on the other hand, describes what proportion of the total electricity consumption is accounted for by self-generated electricity.

$$I_{\text{sc}} = \frac{P_{\text{generation}} - P_{\text{feed in}}}{P_{\text{generation}}} \quad (1)$$

$$I_{ss} = \frac{E_{\text{consumption}} - E_{\text{grid purchases}}}{E_{\text{consumption}}} \quad (2)$$

From the definitions, it is clear that a high degree of self-sufficiency does not necessarily result from a high level of internal consumption. For example, small PV systems with battery storage lead to a high degree of self-consumption. Especially in winter, however, such a system can only cover a part of the total consumption, which leads to a low degree of self-sufficiency. Both indicators are sensitive to the temporal resolution of the underlying measurement or simulation data. The investigation [Hall, 2018] within the framework of IEA Annex 67 showed that a change from 1-minute to 15- or 60-minute measurement resolution changes the indicator of the degree of self-sufficiency by 5% or 10%. This shows that information on the degree of self-sufficiency is only meaningful in the context of the integration period. If a battery storage is used, the changes are negligible.

For the houses participating in the SDE 2014, Figure 11-2 shows the quantities of electricity generated or fed into the grid in relation to consumption. It can be seen that the amount of electricity generated (blue data points) is always greater than the amount fed into the grid. The distance between the points forms the internal consumption. The zero balance line, which is also shown, indicates which teams have managed to achieve a balanced or even positive energy balance with their houses.

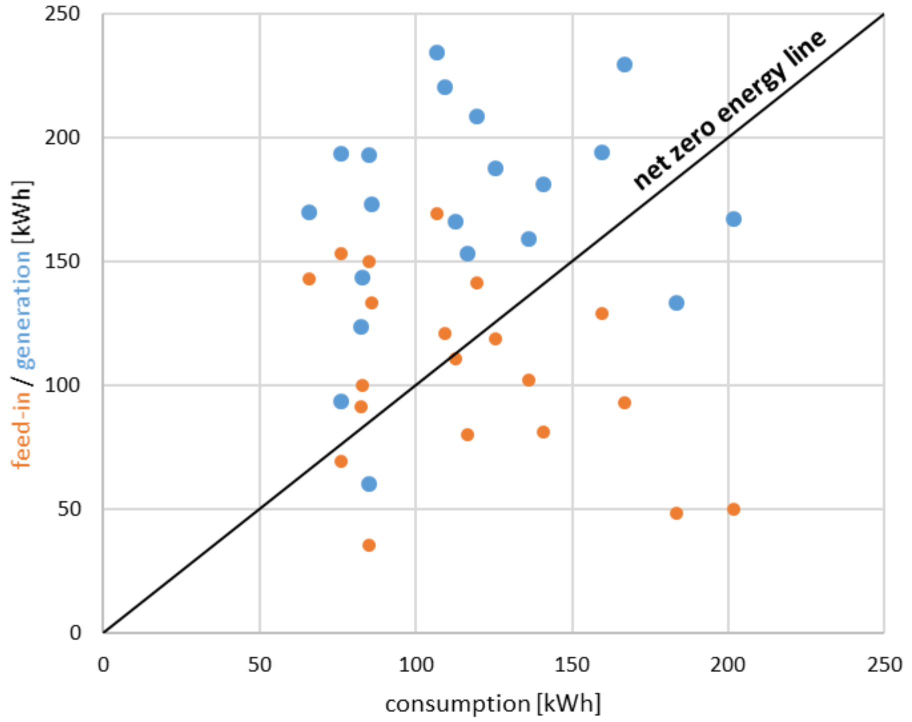

Figure 11-2: SDE14 electrical energy balances of the 20 exhibited buildings during the competition period, (1 min resolution). Source: University of Wuppertal, Moritz Stark

Table 11-1 shows sub contests from the 2014, 2018, 2019, and 2021 Solar Decathlon issues that address energy flexibility. It can be seen that over the years the number, orientation, and weighting of the tasks have remained approximately the same in absolute terms. The subtasks can be roughly divided into two categories: on the one hand, the avoidance of peak loads and, on the other hand, the time shift in electricity consumption due to the introduction of a time-variable electricity tariff.

Table 11-1: Subtasks geared towards energy flexibility in Solar Decathlon competitions

competition	sub contests	**points**
SDE14	House adjustment to network load state	20
	Power peaks [SDE14]	15
SDME18	Demand response [SDME18]	20
SDE19	House adjustment to network load state	20
	Power peaks [SDE19]	15
SDE21	Grid interaction (privileged feed-In, demand-side management) [SDE21]	30

In SDE 2014 and SDE 2019, the energy-flexible subtasks dealt with the avoidance of peak loads and the consideration of electricity tariffs. The latter were rigid and consisted of a high and a low tariff phase. Teams were thus rewarded for avoiding electricity consumption in the evening hours or feeding additional energy into the low-voltage grid. In SDME 2018, on the other hand, the "demand response" subtask was only used to encourage a shift away from the midday and afternoon hours; there was no reward for feeding electricity into the grid at specific time intervals.
In order to perform well in SDE 2021, it will be necessary to use building management systems and to react to requirements that are much more variable in terms of time than before. The teams only receive information one day in advance about how electricity costs will change during the course of the following day (day ahead signal). In addition, the teams have to prove that they can distribute their consumption on the following day so flexibly that a noticeable reduction in power consumption can be observed in the morning hours.

Figure 11-3 shows the point distribution of the energy-related subtasks over the course of the competition history. In order to achieve the full number of points in the energy balance subtask in previous competitions, it was sufficient to show a balanced balance. However, due to the low electrical consumption and the summer climate, this was relatively easy to achieve, see Figure 11-2. In order to promote the further development of proven construction methods (Passive House Standard) and new innovative concepts, it would be useful to integrate the subtask energy balance into the area-related consumption. A positive balance should be the basic prerequisite for achieving points.

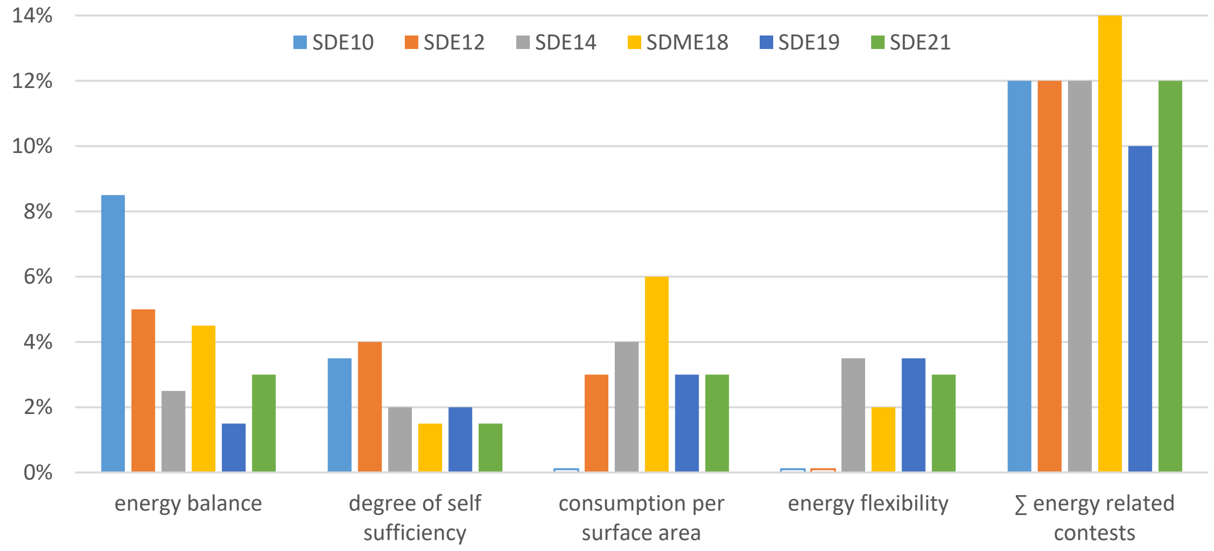

Figure 11-3 : Achievable maximum number of points of the energy flexibility subtasks in relation to the total number of points of the competition (1000 points). Source: University of Wuppertal, Moritz Stark

The fact that any form of energy storage is lossy was only considered of secondary importance in previous editions of the Solar Decathlon. For example, restrictions on maximum battery capacity were always team-independent and static. A sensible, often smaller dimensioning had a negative effect on the energy-flexible subtasks and the degree of self-sufficiency. However, the CO_2 savings gained from flexibility and intermediate storage must be compared to the overall higher energy consumption and the CO_2 backpack of the battery. In future competitions, the teams should therefore justify the selected battery size.
Autarky was rated almost equally in all competitions. The team with the best value received the most points regardless of the achieved result. A more sensible solution for future competitions would be the definition of an (individual) target value that has to be reached to obtain the maximum number of points. The calculation of an optimal degree of self-sufficiency, e.g. in terms of investment costs, is a current research effort [Bandyopadhyay, 2020].
Aspects such as balancing demand, generation and storage, which are advantageous for the dimensioning and function of the electricity grid, will continue to be relevant research areas. Scientific studies already show that the Solar Decathlon is suitable as a case study [Matallanas, 2014].

11.3 Indicators

Due to current research efforts, there are numerous indicators for the evaluation of building flexibility, none of which has yet attained general validity. Within the framework of the IEA EBC Annex 67, an extensive literature search was carried out in which the flexibility function, which will be examined in more detail below, was particularly prominent [Marszal, 2019]. The work is currently being expanded to the neighborhood scale in Annex 82. Further studies on the practical applicability of the methodology are currently being conducted.

In [Junker, 2018], the energy flexibility of a building is defined as the ability to adapt consumption and generation to climatic conditions and grid requirements without compromising comfort conditions. Load management systems are to be encouraged by a cost function to work in a grid-serving manner and to use electricity from renewable energy sources more frequently. It is not static, but is adapted to strongly and less volatile factors, such as the share of renewables in the electricity mix.
How a building reacts to a sudden change in the cost function is described by a flexibility function. This corresponds to a step response and is different for each building. Figure 11-4 shows an example of how a building reacts to an increase in the cost function. After the increase, consumption is reduced noticeably and kept at a low level for some time. Despite the increased cost function, consumption rises again after some time in order not to violate the comfort limits of the building, e.g. the minimum temperature.
The energy flexibility or flexibility function is characterized by properties that are assigned to three essential areas:

- the shifted amount of energy,
- the temporal performance and
- the resulting savings.

The energy quantity evaluates how much energy can be shifted within a defined time period. The temporal performance describes how fast and long a system can react.

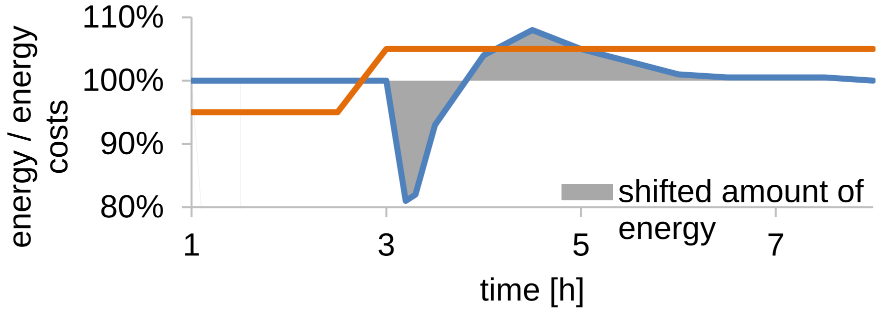

Figure 11-4 : Flexibility function cf. Junker 2018]

A further approach to evaluate the energy flexibility of buildings was presented in [Voss, 2010]. This publication distinguishes between a Load Match Index (Formula (3)) and a Grid Interaction Index (Formula (4)). Both indicators are percentage values and especially take into account the temporal behavior, since they have to be formed for a time interval i.

$$f_{load,i} = \min\left[1, \frac{on\ site\ generation + battery\ balance}{load}\right] \cdot 100\ [\%] \quad (3)$$

$$f_{grid,i} = \frac{net\ grid}{\max|net\ grid|} \cdot 100\ [\%] \quad (4)$$

The Load Match Index puts the energy produced in relation to the energy consumed. The houses shown at the Solar Decathlon are increasingly designed in such a way that they can be balanced or even operated positively over the year, in both cases the index would be 100%. In contrast to the often common consideration of energy quantities, the Grid Interaction Index describes the dynamic or temporal exchange with the power grid. A strongly fluctuating and unsteady consumption behavior that puts a strain on the power grid leads to a high index.
The indicators presented so far have been largely independent of external parameters. This is contrasted by an indicator presented in [Klein, 2014]. This indicator evaluates the consumption with regard to various target values, such as the electricity price or the share of renewable energies in the electricity mix.

$$R_{\mathrm{x}} = \frac{\int P_{\mathrm{el}} \cdot k_{\mathrm{x}}(t)\, dt}{W_{\mathrm{el}} \cdot \overline{k_{\mathrm{x}}}} \quad (5)$$

P_{el} denotes the electrical power of the consumers and k_x the weighting function for the target variable x, $\bar{k}_x$ their temporal average and W_{el} the total energy consumed. If, for example, the electricity price is selected as the target value, k_x (t) represents the instantaneous value of the electricity price for each time step within the considered interval. If the building is operated inflexibly, a value of $R_x = 1$ results. Only when favorable tariff phases are exploited by load management, values of $R_x < 1$ can be achieved.

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12. Building Operation and User Friendliness

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12.1 General Relevance

We are currently in the era of the 4th industrial revolution (Industry 4.0) with the ongoing automation of industrial practices using "smart technologies". The Internet of Things (IoT) is commonly integrated for increased automation and to diagnose issues using less and less human intervention. The building operations cannot be excluded from this trend either. It was common for occupants to interact directly with building systems for example to control heating- or ventilation-systems. With the rise of automation and buildings becoming more complex over time, these basic building operations often take place outside of the users' room or even sometime outside of the building itself. Energy consumption and indoor comfort are two examples of building operations that can benefit from advanced automation. However, some research has shown that fully automating all these functions may not always lead to the most satisfactory operations [1, 2]. The workload for these operations needs to be harmonized with the automation level [3]. Moreover, human-building interfaces play an ever-increasing role. In order for the user to understand and operate the building adequately, it is essential to provide suitable designs for the interfaces, such as embedding in the building or as mobile applications.

12.2 Building & Home Automation Technologies

The following definition of "building automation and control system" is given by the European Directive (EU) 2018/844 [11]: "a system comprising all products, software and engineering services that can support energy efficient, economical and safe operation of technical building systems through automatic controls and by facilitating the manual management of those technical building systems". Most office and public buildings are equipped with this type of system, whereas the level of automation in residential buildings is usually quite rudimentary.

More and more buildings are qualified as "smart buildings" despite the lack of a clear definition of this concept. The European Directive (EU) 2018/844 [11] amending the Directive 2010/31/EU on the energy performance of buildings introduces a common general framework for rating the smart readiness of buildings. A consortium has worked under the authority of the European Commission DG Energy to define an appropriate definition of a smart readiness indicator and the methodology by which it is to be calculated [12]. The proposed approach is mainly driven by considerations related to integration, monitoring and optimization of technical building systems and the potential of energy flexibility of smart buildings in interaction with green power grids.

Another approach is proposed by market players who target directly the end user in a business to consumer (B2C) model. In this type of model, the end user is responsible for the installation and configuration of systems and applications. This model has been made possible by the marketing of numerous connected objects and the widespread use of smartphones. A "smart home" system typically connects controlled devices to a central hub (or gateway). A user interface helps the occupants to control the system via mobile phones, tablets, web-app or wall-mounted terminals.

There are numerous services that can be provided by smart homes and buildings in different domains. These services include:

- Heating, ventilation and air conditioning (HVAC) control through energy metering and air quality monitoring system as well as weather forecast integration.
- Shading system control.
- Lighting control system controlled with mobile application or smart speakers.
- Occupancy-aware control system that enables building operation optimization by using detection sensors, smart meters or environmental sensors like CO_2 sensors.
- Security and risk management: intrusion detection, water leak detection, smoke detection.
- Remote care and monitoring for elderly people, babies, children or even pets.
- Access rights through smart locks or connected intercom.
- Behavior learning and adaption, etc.

Smart speakers integrating a voice assistant (Alexa, Google Assistant, Siri, etc.) are becoming increasingly popular and can be used today as a user interface to control a wide range of devices.

12.3 Wired and Wireless Solutions

Building automation has historically developed based on wired communication protocols. Among the most common, one may mention metering protocols like M-Bus, domain specific protocols like DALI (for lighting) and more "universal" protocols like BACnet, Modbus or KNX. As the Internet has evolved, the main existing wired communication protocols have developed IP gateways to take advantage of the advantages of IP networks.

Wireless solutions are widely popular and are setting the trend today. The reason of the shifting from wired to wireless is mainly cost-driven. Indeed, a wired installation will be more expensive than a wireless one (due to installation charges and cabling). Wireless network on the contrary is less costly and aids in favor of the installation time and flexibility. Wireless technologies are subject to coverage issues (dark spots inside a home where the signal is weak) and power supply issues (energy harvesting or battery-powered sensors). Concerning IT security issues, wireless networks are increasing the attack surface and are intrinsically more vulnerable than wired connection, even if wired networks do also have vulnerabilities. Wireless solutions might also be more subject to obsolescence than wired solutions.

There are multiple wireless communication solutions found in buildings. They can be classified according to different characteristics (range, used frequency, power consumption, network typology, provided "by the building" or by an external service, open or proprietary). Z-Wave, EnOcean, Zigbee, Bluetooth Low Energy are wireless communication protocols often found in smart-buildings and smart-home solutions. WiFi is also used even though it did not, until very recently, allow low-power solution. On the long-range low-power side, LoRa-WAN as a low frequency solution used e.g. for remote meter access should be mentioned. Direct connections to cellular networks (4G, 5G) are also sometimes used.

There are many suppliers in this dynamic economic sector, whether for building automation systems or smart home solutions.

12.4 IT Security and Data Protection Issues

A topic to be addressed is the problem of security, data security and data privacy. Building automation systems can be complex and thus need a systematic approach to provide system integrity and data protection. It is essential to protect the system against attacks at the backbone level (which connects multiple control subnetworks) and the control level. Attackers from a public network must not gain unauthorized access to the system. Likewise, the inner network must be protected against local attacks. Various security mechanisms must be implemented: obviously, data communication process must be secured as well as preventing unauthorized use of the management services. Thus, the key elements which form the basis for both type of secure communication are an authentication mechanism and a secure transmission channel [17].

This secure transmission channel is necessary to protect the transmission of data between authenticated participants against malicious interference. It vows to provide data confidentiality and integrity. This secure

channel can be provided by cryptographic algorithms which use secret keys. This use adds a new layer of security, the key management, which must be considered. Furthermore, a building automation system need to run stable for a long period of time. Thus, such a system also needs an update mechanism [16]. Meyer and al. [20] provide a useful threat-model for building and home automation. Regarding cost efficiency of small automation systems these linked necessary processes could be a bottleneck.
In addition to data breaches, there is also the risk of improper data use [18]. The last few years has seen growing concerns towards data privacy as consumers are approaching connected devices with caution. The European Union's General Data Protection Regulation (GDPR), which took effect in May 2018, requires all companies that do business online with or market to individuals in the Schengen area to take extra steps to protect users' personal information. This regulation requires the companies to:

- explain what user data will be collected and how it will be used;
- ask individuals to give clear consent to have their data collected;
- allow individuals to submit requests to have their data deleted;
- safeguard any collected data and promptly notify users of data breaches.

This regulation requires not only the provision of a secure transmission channel, but also the design of building solutions with data protection and security in mind. Cybersecurity must not only be considered from a cost and value perspective but also from a legal perspective.

12.5 Impact of User Behavior

Human behavior in relation to buildings can be defined as followed according to Polinder and al. [9]: *"observable actions or reactions of a person in response to external or internal stimuli, or respectively actions or reactions of a person to adapt to ambient environmental conditions such as temperature, indoor air quality and sunlight".* Internal stimuli come from within the occupant and include biological and socio-psychological factors. External stimuli come from factors such as building characteristics, technological innovation, policy contexts or cultural and social practices. These stimuli should be taken into consideration in order to motivate the occupants to use the interface that should give them perceived control over the indoor environment and lead to a more desirable indoor experience. Numerous studies have sought to better understand the impact of user behavior on the performance of buildings, particularly in terms of energy efficiency and to find ways to influence it [13].

12.6 User-Building Interaction

A building user-interface can be described as anything the occupant can interact with to get building-related information or to modify parameters or states of building elements and systems such as HVAC-systems, lighting, openings, solar-protections, energy management or any other building services. It can offer occupants a certain degree of freedom to directly or indirectly control the indoor environment with varying levels of automation [8]. However, some research has shown that fully automating all the functions often does not lead to the most satisfactory operations [1-2]. Ideally, the level of automation should be adjusted to functions that the user deems less important and those that require repetitive or tedious actions. The goal is to harmonize the automation level with the physical and/or mental workload needed for the functions.

Figure 12-1: Typical low-voltage pushbuttons as part of the building automation system to replace classical switches for AC wiring (SDE 2012). Source: University of Wuppertal

Figure 12-2: Turning knob to manually adjust the set point for a CO2-controlled ventilation system (SDME 2018). Source: University of Wuppertal

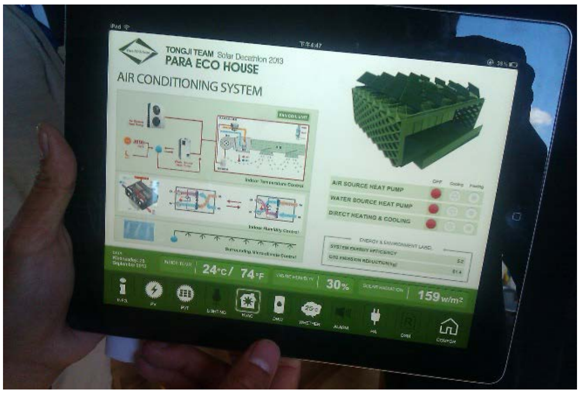

Figure 12-3: User interface for operating the HVAC system in the Tongji team house at SDE 2012. Source: University of Wuppertal

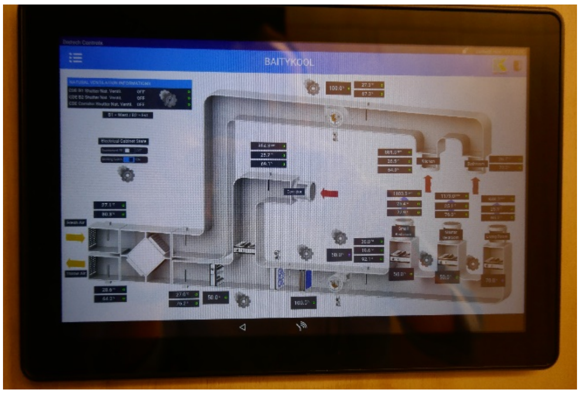

Figure 12-4: Graphic display of the building automation system for the Baitycool team at SDME 2018 in Dubai. Source: University of Wuppertal

More recently, Ahmadi-Karvigh and al. [19] studied the preferences of building users for several tasks and for different level of automation (full automation, adaptive automation, inquisitive automation, no automation at all). The results show that acceptance of high automation levels is quite high for tasks such as “turning off unneeded lights” or “turning off unneeded appliances” whereas the level of acceptance is much lower for tasks such as “rescheduling an activity (washer and dryer)”. A well-thought user participation strategy is recommended to increase acceptance levels of building- and home-automation.

12.7 User Interface Design

There have been a lot of research with a focus on building system (such as heating, ventilation, air conditioning and lighting), occupant behavior and comfort [4-7]. However, there is not much to be found on building interfaces and how their design and underlying logic impact their usability and occupants’ perceived control as well as the resulting comfort and energy performance. Interface design might be a mature topic in human-computer interaction, but many characteristics make building interfaces different than the one used in vehicle dashboards or smart-phone applications for example. The building design process is fast paced: interface selection may receive little attention as designers and builders try to focus on cost and project schedules. Often, decisions about interfaces are made on-site with little in-depth thought about occupants. A more holistic understanding of building interface characteristics and associated occupant behavior is therefore critical. Ultimately, the design of interfaces impacts how occupants use these interfaces and perceive control of the space and building they live in. The ISO 9241 family of standards may be mentioned as a reference related to the question of ergonomics of human-system interaction.

12.8 Relevance in Building Competitions & Living Labs

With the evolution of technology, an increasing level of automation has appeared in building systems. While building automation systems have been used in commercial buildings for several decades, their use in the residential sector is more recent. Security systems (cameras) and smart-meters applications were the main initial market drivers. As these systems become more sophisticated, uncertainty remains as to the optimal level of automation to achieve building performance objectives and occupant satisfaction. The question is not only whether manual or automatic systems result in a more pleasant indoor environment, but also whether they give the occupants the perception of control over the indoor environment. Building competitions and living labs are great experimentation places for this emerging research topic fueled by the fast development of IoT. Such real-size experimentations offer the opportunity to study the functionality, adequacy, reliability of building- and home-automation systems with users and visitors. To the authors knowledge, Solar Decathlon Wuppertal [14] would be the first building competition to introduce the “user-friendliness” as a specific contest. Alavi and al. [15] provide insight related to the evolution of living labs concepts in human-computer interaction and discuss the “raison d’être and future position of the living lab as a method within HCI (human-computer interface) research and design and in relation to advances in sensing technologies and the emerging world of intelligent built environments”. The article distinguishes different type of living labs labelled “Visited Places”, “Instrumented Places”, “Instrumented People”, “Lived-in Places”, and “Innovation Spaces”. Building competitions such as Solar Decathlon offer valuable context to provide building operation data (instrumented places) and feedbacks from users and visitors (visited places) while being less adequate for the other types of studies.

12.9 Feedbacks and Monitoring

Increased presence of automated control in buildings gives the opportunity of collecting more granular and useful data thanks to modern sensors. Furthermore, the provision of information to occupants through feedback mechanisms can impact key building outcomes. Occupants receive feedback through interactions with the building interface and through experiencing the outcomes of actions in the room. Feedbacks can then enable the occupants to learn, understand, interpret, motivate, and/or interact in and with buildings and information can be disseminated visually, auditorily or even haptically, depending on contextual need and available technology. Feedback plays a crucial role in occupants’ perception, interaction, and engagement in buildings for sustainable adaptive strategies – particularly for slow responding (e.g., thermal) systems [10]. Moreover, interactions between users and buildings elements, systems and interfaces can be monitored to provide feedback to architects and engineers about the real acceptance and use of the designed solutions.

12.10 Proposition of a Framework to assess User Experience

A framework to assess user experience while operating a building must consider the diversity of possible strategies and interfaces, from fully passive and low-tech design to highly automated solutions. A user-building interface strategy shall at the end be assessed by end-users to understand its qualities and shortcomings. The users should be able to give their feedback on the overall strategy and its implementation as well as evaluate domain-specific aspects. The main domain-specific aspects to be addressed are (1) control of indoor climate and air quality, (2) control of shading and lighting, (3) energy management, (4) multimedia and other additional smart-home services (e.g. connected intercom, smart speakers). Overall assessment should cover aspects related to (a) general effectiveness and relevance, (b) reliability and usability, (c) self-descriptiveness[19], (d) controllability, (e) adaptability and flexibility, (f) consideration of

[19] “An object or an interface is self-descriptive if users realize what they can do with it, and how they can do it. At any time, users are aware what is happening and how to interact with the object or interface. Thereby, the ultimate goal is that a product explains itself

disabilities and specific categories of users, (g) data protection and safety, (h) user awareness and empowerment, (i) innovation.
Specific questions may be asked for these different aspects:

- General effectiveness and relevance (overall)
  - Is the overall building-user interface strategy readable and understandable?
  - Is the overall building-user interface strategy coherent with the overall design approach of the building?
  - Are the means put in place appropriate and adjusted to the needs and to the expected outcome? (efficiency, including energy efficiency)
- Adaptability and flexibility (overall)
  - Are the interfaces adaptable to user preferences?
  - Can the interfaces integrate evolutions of the building and its sub-systems?
- Consideration of disabilities and specific categories of users (overall)
  - Are the interfaces adapted to users with disabilities (e.g. person in wheelchair or blind person)?
  - Are the interfaces adapted to specific categories of users (kids, elderly people)?
- Data protection and safety (overall)
  - How is the data protection issue tackled?
  - How is the system and data safety considered and tested?
- User awareness and empowerment (overall)
  - Do the interfaces generate awareness about optimal building use?
  - Do the interfaces induce a sense of empowerment and control?
- Innovation (overall)
  - Do the proposed interfaces integrate innovative approaches and/or technologies?
- Reliability and usability (per domain)
  - Are the interfaces functioning in a reliable manner?
  - Are the interfaces sufficiently responsive and convenient to use?
  - Are several languages available?
- Self-descriptiveness (per domain)
  - Can the interfaces be used without prior knowledge?
  - How intuitive are the interfaces?
- Controllability (per domain)
  - Are the users able to control their interactions with the building? (i.e. to start, stop or cancel actions and be aware of current status or ongoing action)

The different topics described above can be evaluated given a level of performance rated from 0 (bad) to 3 (excellent). In the evaluation grid suggested bellow in Figure 12-5 and Figure 12-6, the overall aspects count for 60% of the total score and four main domains (indoor climate and air quality, shading and lighting, energy management, multimedia and other services) count for 10% each.

without the need of any instructions or written hints for its users." https://www.usability.de/en/usability-user-experience/glossary/self-descriptiveness.html

	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 12-5 : 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

	part of total score		Level 0	Level 1	Level 2	Level 3	Score
Indoor climate and air quality	10%	Reliability and usability	Not convinient, not responsive. Major bugs. Not reliable	Fairly convinient, reliable and responsive. Minor bugs	Intuitive and responsive. No apparent bugs. Clear navigation	Very high level of userfriendliness	3
		Self-desciptiveness	Not understandable	Most of the functions are understandable	Built-in tutorial, self-explanatory	High level of intuitiveness. Informations and functions are very clear	2
		Controllability	No user feedback or control	User has some control	Awareness of ongoing actions and good control	Very good mix of automation, control and awareness	1
Shading and lighting	10%	Reliability and usability	Not convinient, not responsive. Major bugs. Not reliable	Fairly convinient, reliable and responsive. Minor bugs	Intuitive and responsive. No apparent bugs. Clear navigation	Very high level of userfriendliness	1
		Self-desciptiveness	Not understandable	Most of the functions are understandable	Built-in tutorial, self-explanatory	High level of intuitiveness. Informations and functions are very clear	2
		Controllability	No user feedback or control	User has some control	Awareness of ongoing actions and good control	Very good mix of automation, control and awareness	0
Energy management	10%	Reliability and usability	Not convinient, not responsive. Major bugs. Not reliable	Fairly convinient, reliable and responsive. Minor bugs	Intuitive and responsive. No apparent bugs. Clear navigation	Very high level of userfriendliness	3
		Self-desciptiveness	Not understandable	Most of the functions are understandable	Built-in tutorial, self-explanatory	High level of intuitiveness. Informations and functions are very clear	3
		Controllability	No user feedback or control	User has some control	Awareness of ongoing actions and good control	Very good mix of automation, control and awareness	3
Multimedia and other services	10%	Reliability and usability	Not convinient, not responsive. Major bugs. Not reliable	Fairly convinient, reliable and responsive. Minor bugs	Intuitive and responsive. No apparent bugs. Clear navigation	Very high level of userfriendliness	0
		Self-desciptiveness	Not understandable	Most of the functions are understandable	Built-in tutorial, self-explanatory	High level of intuitiveness. Informations and functions are very clear	0
		Controllability	No user feedback or control	User has some control	Awareness of ongoing actions and good control	Very good mix of automation, control and awareness	1

Figure 12-6 : Suggestion for the domain-specific part of an evaluation grid to be used within a competition context; in this example, 4 levels of performance are defined for each indicator

12.11Further Reading

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Abbreviations

Table List of frequently used abbreviations

Abbreviations	Meaning
DHW	Domestic hot water
EN	European Norm
EPBD	Energy Performance of Buildings Directive
GHG	Greenhouse gas
HP	Heat pump
GWP	Global warming potential
IEA EBC	Energy in Buildings and Communities Programme of the International Energy Agency
kWh	Kilowatt hours: 1 kWh = 3.6 MJ
λ	Lambda-value (value for the insulating capacity of a material)
LC	Life cycle
MJ	Mega joule; 1 kWh = 3.6 MJ
NRE	Non-renewable energy (fossil, nuclear, wood from primary forests)
NZEB	Nearly zero energy building or nearly zero emissions building
PE	Primary energy
PT	Portugal
PV	Photovoltaic (cell or panel)
Ref	Reference
RES	Renewable energy sources
SFB	Single family building
U-value	Thermal transmittance of a building element

Definitions

Definitions of energy performance according to EN 15603:2008 (Official Journal of the EU, 19.4. 2012, p. C 115/9) and econcept (embodied energy):

Energy source: source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process.

Energy carrier: substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes.

System boundary: boundary that includes within it all areas associated with the building (both inside and outside the building) where energy is consumed or produced.

Energy need for heating or cooling: heat to be delivered to or extracted from a conditioned space to maintain intended temperature conditions during a given period of time.

Energy need for domestic hot water: heat to be delivered to the needed amount of domestic hot water to raise its temperature from the cold network temperature to the prefixed delivery temperature at the delivery point.

Energy use for space heating or cooling or domestic hot water: energy input to the heating, cooling or hot water system to satisfy the energy need for heating, cooling or hot water respectively.

Energy use for ventilation: electrical energy input to the ventilation system for air transport and heat recovery (not including the energy input for preheating the air).

Energy use for lighting: electrical energy input to the lighting system.

Renewable energy: energy from sources that are not depleted by extraction, such as solar energy (thermal and photovoltaic), wind, water power, renewed biomass. (definition different from the one used in Directive 2010/31/EU).

Delivered energy: energy, expressed per energy carrier, supplied to the technical building systems through the system boundary, to satisfy the uses taken into account (heating, cooling, ventilation, domestic hot water, lighting, appliances, etc.).

Embodied energy: Comprises the cumulated primary energy demand for production, transportation and disposal of building components, appliances, renewable energy generation units and building construction measures within building renovation.

Exported energy: Energy, expressed per energy carrier, delivered by the technical building systems through the system boundary and used outside the system boundary.
Primary energy: Energy found in the nature that has not been subject to any conversion or transformation process. It is energy contained in raw fuels and other forms of energy received as input. It can be non-renewable or renewable.

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