Design Guidelines

IEA SHC TASK 56 | Building Integrated Solar Envelope Systems for HVAC and Lighting

Design Guidelines

Deliverable DC.3

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IEA Solar Heating and Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is *"To enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050."*

The members of the IEA SHC collaborate on projects (referred to as Tasks) in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

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- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat for Industrial or Agricultural Processes (Tasks 29, 33, 49, 62, 64)
- Solar District Heating (Tasks 7, 45, 55)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63)
- Solar Thermal & PV (Tasks 16, 35, 60)
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Contents

Acronyms

Acronym	Description
AT	Treated Area
BIPV	Building Integrated Photovoltaics
BIPVT	Building Integrated Photovoltaic Thermal
BISES	Building Integrated Solar Envelope System
BIST	Building Integrated Solar Thermal
CD	Cooling Demand
CFD	Computational Fluid Dynamic
CL	Cooling Load
DA	Daylight Autonomy
DAL	Dalec (simulation software)
DE	Direct Electric
DGP	Discomfort Glare Probability
DH	District Heating
DHW	Domestic Hot Water
EP	Energyplus (simulation software)
EPBD	Energy Performance of Building Directive
ERV	Energy Recovery Ventilation
EU	European Union
FE	Final Energy
FEN	Ferner (simulation software)
GUI	Graphical User Interface
GW	Groundwater
HD	Heating Demand
HL	Heating Load
HP	Heat Pump
HRV	Heat Recovery Ventilation
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Ai Quality
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCF	Load Cover Factor
LED	Light Emitting Diode
LEH	Low-Energy House
MFH	Multi-Family House

Acronym	Description
MOD	Modelica LBNL Buildings Library
MVHR	Mechanical Ventilation with Heat Recovery
nZEB	Nearly-Zero Energy Building
NZEB	Net-Zero Energy Building
PE	Primary Energy
PER	Primary Energy Ratio
PH	Passive House
PHPP	Passive House Planning Package
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PV	Photovoltaic Panels
PVT	Photovoltaic Thermal
RE	Renewable Energy
ROI	Return on Investment
SC	Self-Consumption
SCF	Supply Cover Factor
SDWR	Shower Drain Water Recovery
SE	Solar Efficiency
SF	Solar Fraction
SFH	Single-Family House
SFP	Specific Fan Power
SHGC	Solar Heat Gain Coefficient
SIM_BO	Simulink Almabuild (simulation software)
SIM_IBK	Simulink Carnotuibk (simulation software)
SP	Self-Production
SPF	Seasonal Performance Factor
ST	Solar Thermal
STVB	Solar Thermal Venetian Blinds
SY	Solar Yield
TC	Thermal Comfort
TRN	TRNSYS (simulation software)
UE	Useful Energy

1 Structure of Subtask C report

In Subtask C of IEA SHC Task 56 complete solar envelope systems based on active and passive components and integrated into the HVAC system are investigated on building level.

Different approaches for investigating **Solar Envelope Systems** are required for residential and office buildings. This report has the goal to describe the different methods used for non-residential (i.e. office) and residential buildings and to give comprehensive information about the reference buildings and HVAC systems used in IEA SHC Task 56.

Report DC.1 gives general information about benchmarks, simulation models of the reference buildings as well as, reference locations and climate analysis, and finally Key Performance Indicators (KPIs). Additionally, an overview of the features of different simulation platforms is given.

Based on this, the Report DC.2 documents the simulation results and consists of two parts:

- Part A presents the simulation results of the office reference building.
- Part B describes the approach for residential buildings. Two examples are described in detail following different approaches.

In this report, **Deliverable DC.3,** a summary of the simulation results is given, and **design guidelines** are provided based on the simulation and monitoring results.

Deliverable DC.4 provides monitoring results of demonstration buildings.

2 Overview of Solar Active Facades

2.1 General aspects

Solar envelope systems have been defined in IEA SHC Task 56 as the envelope systems entailing elements that use and/or control incident solar energy, having one or more of the following uses:

- To deliver renewable thermal or/and electric energy to the systems providing heating, cooling, and ventilation to buildings.
- To reduce heating and cooling demands of buildings, while controlling daylight.

Although this definition is clear in describing the distinguishing feature of solar envelope solutions, the scope remains wide in terms of technologies that can be applied. It includes indeed a very diversified group of solutions, from the ones managing daylighting and solar gains (mainly shading devices) to others that integrate renewables source generation (mainly PV, ST, or PVT). Such systems can be also coupled with other active components (mechanical ventilation with heat recovery, heat pumps, etc.) leading to a broad variety and wide range of solutions and applications.


Figure 2-1. Examples of solar envelope systems described in Deliverable DA1+2. From the top, Kromatix BIPV panels, Lumiduct, Okalux Okasolar 3D, Kindow, and SunRise building-integrated solar thermal system.

Solar envelopes might involve passive elements (i.e. shading, daylight control) and/or active elements (BIPV, BIST, BIPVT). Façades with elements for daylighting/shading, glare protection (solar gains, artificial light) are mainly applied in non-residential buildings and are able to:

- guarantee visual comfort (while thermal comfort is maintained);
- increase daylight use;
- enable primary energy savings (by reducing heating demand and cooling demand).

Façades with active elements (i.e. Solar Thermal (ST), Building Integrated Solar Thermal (BIST), Photovoltaic Thermal (PVT) or Heat Pump (HP) and/or Heat Recovery Ventilation/Energy Recovery Ventilation (HRV/ERV) coupled with PV, Building Integrated Photovoltaic (BIPV)) for heating/cooling/ventilation can be applied in both residential and non-residential buildings to:

- guarantee thermal comfort and provide indoor air quality;
- allow for primary energy savings (reduction of heating and cooling demand as well as maximization of renewable energy use).

When an office building is considered, simplifications and assumptions on building geometry and user behaviour are necessary and a good trade-off between the accuracy of the model and the computational effort has to be found. The reference building approach, using a well described office cell located in different climates has been chosen: the first step consists in simplifying a real building geometry by identifying elementary modules. A second simplification consists in assuming that the energy behaviour of the reference floor can be assimilated to that of a series of reference office cells oriented according to the building's exposures. The validity of this depends in deed on the floor area and the building's aspect ratio. Occupancy (number of people, activity level, hourly schedule, etc.), appliances, lighting, shading, ventilation, and infiltration have to be defined accurately. As an example, detailed values are shown in DC.1 Section 3.3.2-3.3.4. Building components, energy system, DHW, and daylight system have been defined as well.

In the residential sector, the application of solar façades is more relevant for multi-family buildings (with relatively small available roof area) than for single-family houses (with relevant roof area with respect to the treated area). The reference building approach cannot be applied easily in residential multi-family buildings because usually, each building is individual (geometry, floor plan, number of floors, heated/unheated cellar, etc.). Furthermore, for residential buildings, the focus is the envelope quality, HVAC performance, and (façade integrated) RE system. Providing high thermal comfort and indoor air quality is a prerequisite (that has to be proven for each technology). Visual comfort (daylighting and glare) is usually not relevant in residential buildings. Depending on the investigated technology, usually either a flat or the entire building has to be considered and it is not trivial to define a common MFH reference building.

In order to understand what solutions or combinations can better satisfy the needs of stakeholders and investors, the expected benefits shall be thoroughly assessed, preferably with the use of quantitative indicators to ease the comparison among different technologies and combinations of technologies on building level. However, this task is not as easy as the value proposition is often multi-variated with weights that differ depending on the interlocutor and a sound methodology for a quantitative assessment still has to be developed.

In this report, different technologies and solutions are discussed and the issue of comparability is tackled through a *cost-optimal* approach, defined in Article 2.14 of the EPBD as the energy performance level which leads to the lowest cost during the estimated economic life-cycle from the financial and macro-economic effects. It is assumed that all the solutions presented in the report satisfy the indoor environmental quality requirements in terms of comfort (air changes, daylighting, and hygrothermal comfort), and thus the comparison is limited to the energy and life-cycle cost (LCC) terms.

2.2 Components of BISES and their integration into the building

For the investigation of BISES on building level the following applications are included:

Table 2-1: Components of Solar Facades, use, and type of system integration.

	Technology	Use	System	remark
1	Insulation	Heat, Cold	-	Passive
2	Windows	Heat, Cold, Daylight	-	Passive
3	Daylighting (blinds, screens, etc)	Shading, glare protection, daylighting	(influence on HD, CD, HL, CL)	Solar Passive
4	(BI)PV	Electricity	Heating, cooling with heat pump, MVHR, E-Boiler, etc. Aux., Appliances	Solar Active
5	(BI)ST	Heat	Heating, DHW, src. for HP Cooling	Solar Active
6	(BI)PVT	Heat, Electricity	Pre-Heating, src. for HP (Heating, DHW, Cooling)	Solar Active
7	MVHR (HRV/ERV)	Heat (Cold), Humidification, Dehumidification	Ventilation, heating, cooling, dehumidification	Active
8	Heat pump	Heat, Cold, Dehumidification	Heating, cooling, DHW, dehumidification	Active
9	Storage	Heat, Electricity	Heating, DHW, Cooling, Aux. Appliances	Passive
10	SDWR	Heat	DHW	Passive
11	Pipes/Ducts		Heat/cold distribution, ventilation	Passive

3 Methodology and Workflow

3.1 Aspects of Building Integrated Solar Envelope Systems (BISES) Simulation

Building integrated solar envelope systems (BISES) include a variety of technologies (PV, ST, PVT, etc.) integrated into the building. Thus, the integration of solar envelope systems contains several aspects. Façade integration has an architectonical and design aspect; furthermore, the building physics aspect has to be considered. Additionally, there is the level of integration into the building HVAC system including thermal and/or electric storage. Here, aspects of thermal (and visual) comfort and indoor air quality are addressed. The focus is on system design and control optimization. Finally, there is the aspect of the building with its energy system into the grid. Keywords are grid interaction and "smart buildings".

Within IEA Task 56 SubT C the focus was the evaluation and optimization of BISES on building level by means of dynamic building, HVAC, and RE simulations. The grid interaction was considered by evaluating the simulation (and monitoring) results in terms of primary energy, using monthly primary energy conversion factors (see section 3.2).

3.2 Why Building, HVAC and RE simulation

The building, HVAC, and RE simulation can include several aspects and have different goals and objectives. Often, simulation is performed to obtain a technology evaluation and or technology ranking with comparable boundary conditions (user behaviour, climate, etc.). The main indicators are system performance and efficiency for a given range of (visual and) thermal comfort (TC) and indoor air (IAQ). Usually, such an investigation includes the techno-economic analysis and a process of optimization.

Because of the complex dependencies und multi-objective nature of the optimization problem, building and system simulation can be a valuable support for designers and decision-makers. Depending on the scope and objective evaluation of BISES can be performed on several levels:

- on component level (e.g. PVT collector performance map)
- (HVAC) system level (e.g. PVT collector as source for heat pump)
- on building (and HVAC) level (e.g. SFH in PH standard with HP with PVT collector)
- on district/city/country level (e.g. grid interaction of SFH in PH standard with …)

Evaluation of BISES should account for the energy system in which the building is operated. In a "fossil" environment the overall benefit will be different compared to a "green" environment. A simplified approach is discussed in the section about monthly primary energy factors.

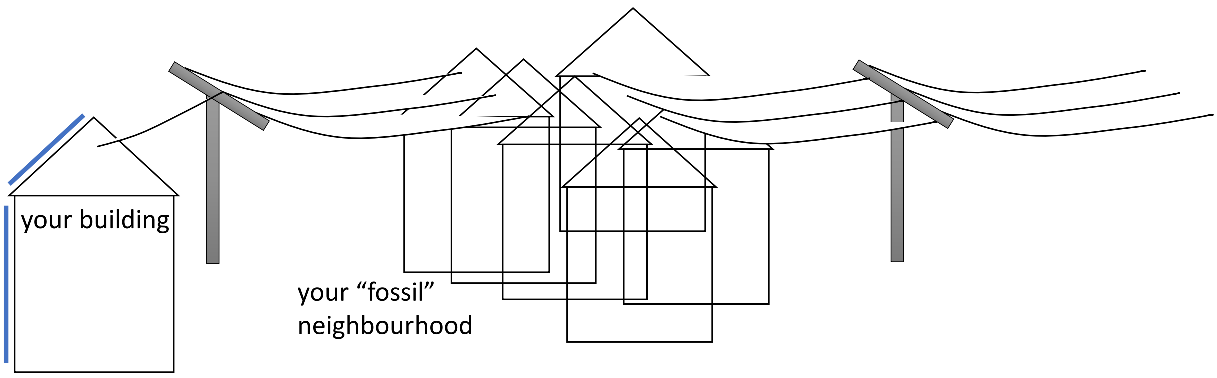


Figure 3-1 Solar Façade in a "fossil" neighbourhood.

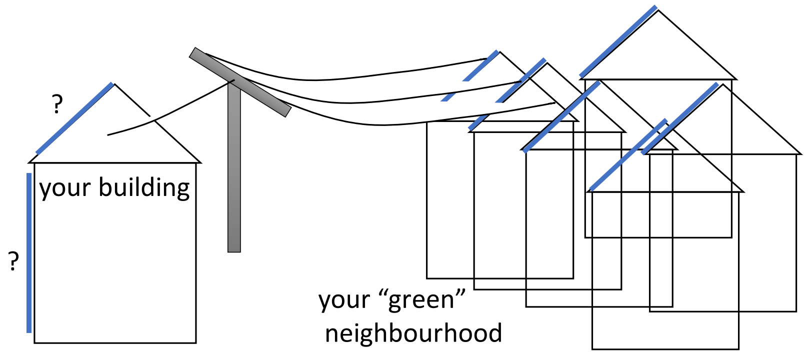


Figure 3-2: Solar Façade in a "green" neighbourhood.

On a component level, optimization addresses:

- Component design and sizing
- System concept and design and
- Control optimization including reduction of aux. energies (fans, pumps, etc.)

Within the IEA SHC Task 56 the main objectives in SubT C are:

- a detailed technical-economic analysis, and
- the assessment of the solar envelope components integration impact for different buildings in different climates

based on (dynamic) building, HVAC, and RE simulation.

The following KPIs were defined to evaluate different systems and system concepts:

- Heating Demand (HD), Heating Load (HL).
- Cooling Demand (CD), Cooling Load (CL).
- Thermal comfort (ϑ_{op}, rH).
- Indoor Air Quality (IAQ, CO_2-concentration).
- Visual Comfort (→ office).
- Load Cover Factor (LCF) and Supply Cover Factor (SCF), Solar Fraction.
- PE/CO_2 savings (non-RE, energy balance including appliances).
- Economics (LCC / annual capitalized cost).

3.3 Techno-Economic Analysis

For the economic evaluation, the annual capitalized cost is determined, and the following economic parameters are required:

- Investment and installation costs.
- Consideration period (20 a).
- The service life of ST, PV, HP, MVHR, etc., replacement and residual value (e.g. after 15 a).
- Interest rate and inflation rate (i = 3 %).
- Energy/electricity price (0.25 €/kWh on average).
- Maintenance costs (e.g. 5% of investment).

3.3.1 The goal of techno-economic analysis and cost-optimality

Usually, the goal of the techno-economic analysis is to identify cost-optimal solutions under certain boundary conditions (e.g. cost parameters) and constraints (e.g. thermal and visual comfort, indoor air quality, max. CO_2 emissions). The techno-economic analysis allows developing a technology ranking on the **macro-economic scale**. Within a **global optimization,** different technologies can be investigated (e.g. integration of storage into the building and its influence on the local, regional, or national energy system). On the **microeconomic scale, individual**

optimization has usually the purpose to find optimal sizing of components (dimensioning) and/or optimize the operation of the building and system (control optimization, commissioning, and fault detection).

A techno-economic analysis can involve two different levels:

- Micro-economic optimization → costs for building owner/operator
(system design/sizing, control, cost reduction).

- Macro-economic evaluation → costs for society
(technology ranking, PE/CO2 savings, costs).

3.3.2 Critical remark on techno-economic analysis and cost-optimality

The design guidelines are based on the results of a techno-economic analysis. Within the framework of IEA SHC Task 56, the methodology of the EU (EPBD, nZEB, cost-optimality) was followed using standard and/or reference conditions.

The *cost-optimal* level is defined in Article 2.14 of the *EPBD* as "the energy performance level which leads to the lowest *cost* during the estimated economic lifecycle" from two different perspectives:

- financial (looking at the investment itself at the building level), and
- macro-economic (looking at the *costs* and benefits of energy efficiency for society as a whole).

Individual recommendations and decisions might deviate from the derived general trends due to

- Comfort and health aspects.
- Individual wishes/opinions/experiences.
- Design/architectural/cultural aspects.
- Local incentives, funding, restrictions (historic, current, and expected).
- Local market/local conditions (availability of technology, price, competition, experience, and skills, etc.).
- Local energy system (DH, electricity mix, biomass, etc.).
- Investment limits.
- etc.

3.4 Solar Efficiency index (SE index)

The benefits of implementing advanced solar facades are difficult to assess given that these technologies often bring about complex interactions with the indoor environment and building energy management systems. The approach chosen in this study [1] is to propose and test a new, simple index called the **Solar Efficiency index** (SE index). This index allows characterizing the performance of solar building envelopes from a holistic perspective and accommodates any type of façade integrated technology or system. The results provided by the index give an overview of how solar energy can positively be used to reduce the energy demand of the whole building as well as it allows evaluating, in the case of renewable energy conversion, the share of the energy that is useful to the building in terms of load matching. This is particularly interesting because it provides a way of understanding if, and how advanced facades can increase the use of solar energy in a building, and from a larger system point of view, how the building can be integrated with the regular energy grid or a local energy grid. One additional strength of this approach is that it is a positive index that communicates the performance of a design without requiring a benchmark performance derived from a second building.

The calculation of the index is carried out with building performance simulation and requires running two separate simulations: a regular energy simulation for the building and the location desired and a second simulation using the same model but a modified weather file in such a way that the diffuse, beam and global horizontal irradiance values are set to null. The formula to calculate the solar efficiency index is then:

$$SE_{index} = \frac{E_{0\,net} - E_{sun\,net}}{E_{0\,net}} \quad [-] \qquad \text{Eq. 3-1}$$

With:

$$E_{0\,net} = \int_{t1}^{t2} e_0(t)\, dt \qquad \text{Eq. 3-2}$$

And:

$$E_{sun\,net} = \int_{t1}^{t2} \left(e_{sun}(t) - i(t)\right) dt \qquad \text{Eq. 3-3}$$

Where $e_0(t)$ [W] and $e_{sun}(t)$ [W] are respectively the power demand required for heating, cooling, and lighting for the building with and without the contribution of solar radiation at the instant t, meaning $e_0(t)$ is obtained in the simulation with the modified weather file. $i(t)$ [W] is the amount of electric power being converted at the instant t by a renewable energy system if applicable.

The calculation of the index can be carried out for each hour of the year or on larger timesteps - such as daily values -if there is a significant load shift due to thermal mass in the building. The results may be presented as cumulated frequencies or frequency distributions which allows visually identifying a higher-performing design (Figure 3-3). Index values in the]0; 1] interval indicate that the building efficiently uses solar radiation to lower its energy use compared to a situation with no solar radiation, while an SE value of 1 means the building is completely self-sustaining (perfect load match). Any value above 1 means excess energy needs to either be fed back to the grid or stored. An SE index value equal to zero implies that either no solar radiation is available, or the building is not able to use solar radiation to reduce its energy demand and values below zero indicate that the building has to use more energy to operate when solar radiation is available than when it is not.

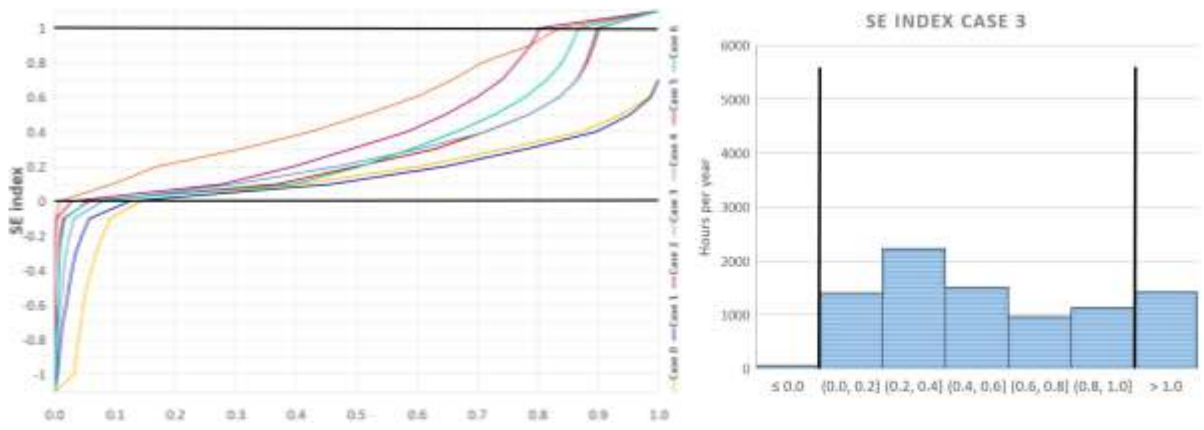


Figure 3-3: Different options to visualize the hourly results of the solar efficiency index calculation for different case studies.

3.5 Monthly Primary Energy Conversion Factors

Sustainable and responsible use of resources is required in order to mitigate climate change. Micro-economic goals usually consider the capitalized investment costs and/or the purchased energy but usually disregard environmental impacts. However, on the macro-economic scale, the aim must be the reduction of the (non-renewable) primary energy (PE) use and CO_2-emissions. There is a need for an appropriate evaluation method for comparing and ranking different passive and active building technologies e.g., according to their impact on PE consumption. National conversion factors for PE/CO_2 differ significantly between different countries, might be influenced by political reasons, and are subject to change. Seasonal variations are not considered at all.

The electricity mix is and will be influenced to a higher extent in the future by the available renewable energy sources, which are hydropower, wind energy, and PV with strong differences in daily and seasonal availability. Without the presence of seasonal storages, fossil fuels will predominantly cover the winter load also in the near and midterm future. The electricity mix is also influenced by the load: buildings, have – in heating-dominated climates - high demand in winter, and lower demand in summer. The share of electricity for heating is still relatively low but will increase with the more widespread use of heat pumps and electric heating. Hence, savings in winter will have a higher value. Remark: to cover the cooling demand in summer by RE is less critical because of the contemporaneity of cooling demand and solar availability.

A PE evaluation method, that allows to include the future development of the load (i.e. building stock) and electricity mix (share of REs) with seasonal variations was developed and applied within the task. The impact on the ranking of different passive and active technologies depending on different scenarios of the energy mix can be shown.

As an example, net-zero energy buildings (NZEB) might not significantly reduce winter grid load but feature excessive PV overproduction in summer. The mismatch between (electricity) demand and PV yield has to be considered.

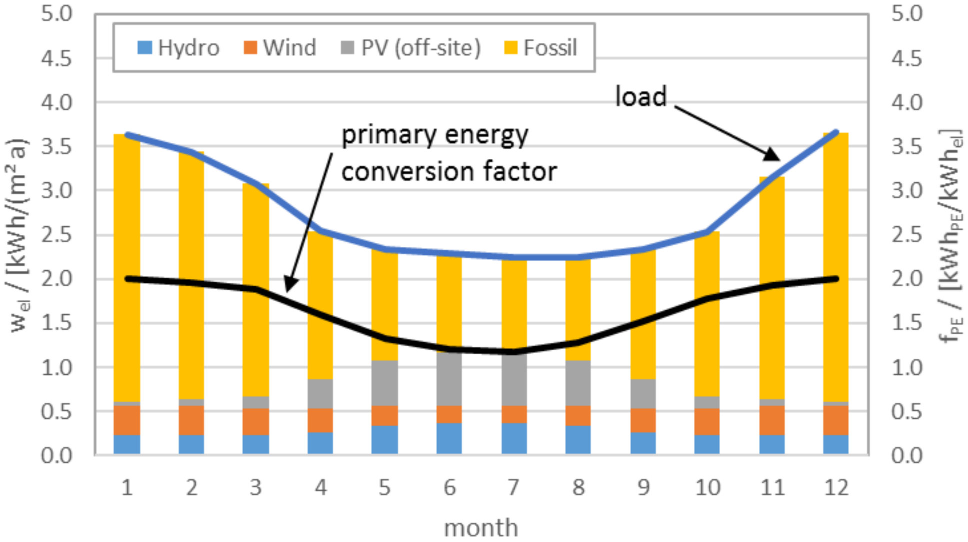


Figure 3-4: Monthly share of renewables (hydro, wind, PV, fossil) and corresponding PE conversion factor, an example of a PH with a HP for heating and DHW supply with a share of 10 % hydro, 10 % wind, 10 % PV and 70 % fossil in the electricity mix.

Table 3-1: Monthly PE conversion factors acc. to Figure 3-4.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	av.
A: 10-10-10	2.01	1.96	1.89	1.60	1.33	1.20	1.18	1.28	1.53	1.78	1.92	2.01	1.6
B: 10-30-30	1.53	1.42	1.23	0.50	0.08	0.08	0.08	0.08	0.33	0.98	1.33	1.54	0.8

4 Demands, Loads, and Solar Potential

4.1 Energy Demand

Understanding the energy demand of a building, i.e. the energy demand for heating, cooling, domestic hot water preparation, auxiliary energies (in particular for ventilation), lighting, and appliances is essential in order to design energy-efficient systems with a high share of renewables. The first step should always be reducing the demand (and load) by means of passive and active measures and then to integrate RE. In order to be able to predict possible savings, the demand has to be predicted correctly, at least on a monthly basis.

4.2 Loads

Predicting Heating and Cooling loads correctly is the basis for appropriate system sizing. Under-sizing can lead to discomfort (under-heating, over-heating) and must be avoided. Contrariwise, oversizing can lead to suboptimal performance, the shorter service life of equipment (on/off cycling) and is furthermore associated with exceeding investment costs.

Traditionally, the energy demand and the load are determined based on experience and include a sufficient safety margin in spite of the fact that there exist several standards. Building simulation can support not only the design of better buildings but also the more precise dimensioning of the HVAC system and thus enabling design with lower investment costs and better performance.

Sizing will directly influence the efficiency of a system and the correct prediction of the Heating Load, and Cooling Load including Dehumidification and Humidification Load is key to obtain high-efficiency levels. The equipment size directly influences the:

- equipment cost,
- compactness (building integration, design, space requirement), and
- sound emissions.

System sizing and rules for system design should include identification of synergies and conflicts between different technologies and should try to avoid conflicts considering:

- prefabrication/industrialization,
- space restrictions, and
- rules for the appropriate coupling of different subsystems,

Building type:

- residential (MFH, SFH),
- office, and
- other (not covered here).

Climate:

- Cold (e.g. Stockholm),
- Moderate (e.g. Stuttgart), and
- Warm (e.g. Rome).

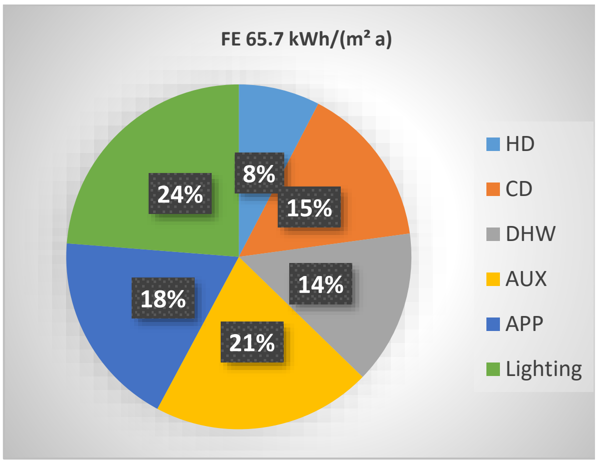
Application (depending on building type and climate).

4.3 Range of final energy demand

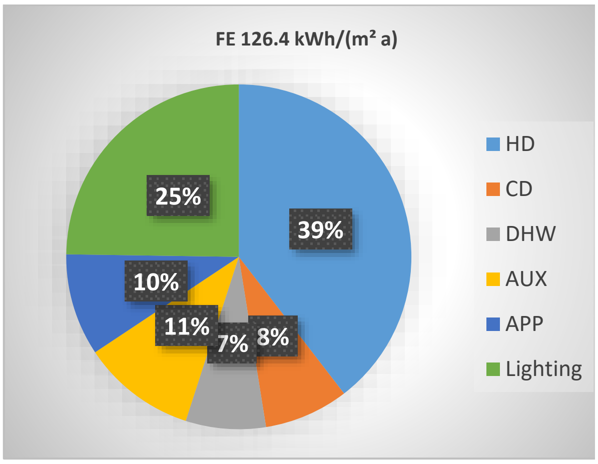
A possible range of final energy demand of a typical office and a typical residential building is shown in the following figure for a moderate climate. While in office buildings lighting and other electric plug loads are dominating, in residential buildings heating and DHW preparation are more relevant. Heating demand in poor-performing residential buildings can have a share of 50% and can be reduced to about 15% in high performing buildings. In high performing residential buildings, DHW has a significant share, and appliances contribute about 50% of the total final energy demand.

Even in moderate climates, there is a significant share of cooling almost independent of the building envelope (but significantly depending on the shading strategy) in office buildings, while active cooling is usually not required in residential buildings.

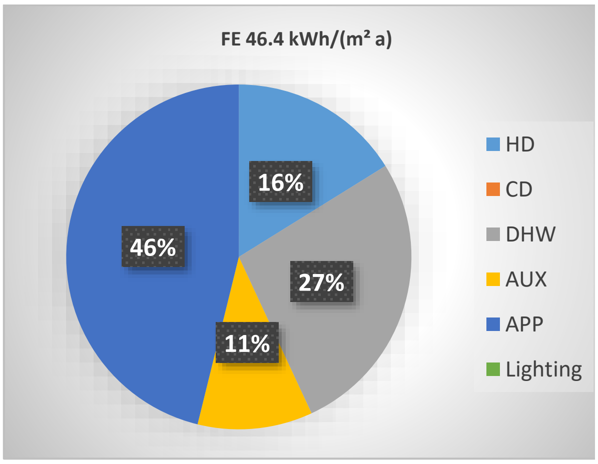
In this example, a high performing building with good envelope, MVHR, heat pump heating, and highly efficient appliances (e.g. LED lights) has "low" demand in the range of 45 $kWh_{el}/(m^2\ a)$ in case of the residential building and approx. 65 $kWh_{el}/(m^2\ a)$ in case of the office. A poor performing building with poor envelope, extract air ventilation and direct electric heating has a "high" demand in the range of 90 $kWh_{el}/(m^2\ a)$ in case of the residential and 125 $kWh_{el}/(m^2\ a)$ in case of the office.



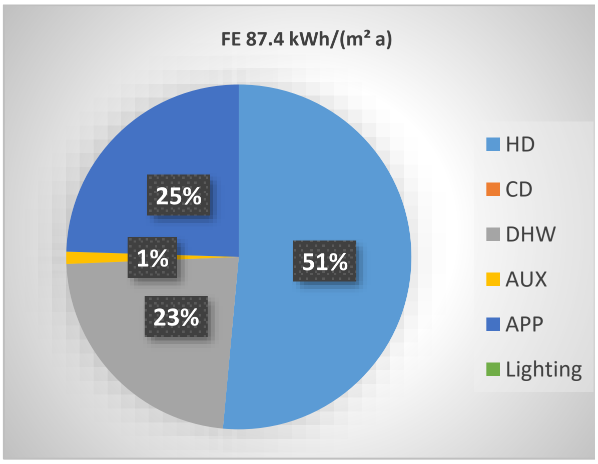
„low" office



„high" office



„low" residential



„high" residential

Figure 4-1: a possible range of final (electric) energy demand of a typical office (top) and a typical residential building (bottom); (left) high performing building with "low" demand; (right) poor-performing building with "high" demand.

While in office buildings a large share of the load (in particular cooling and also lighting) occurs during daytime (i.e. during the presence hours of persons), in residential buildings the load is distributed more evenly. Remark: Additional loads from elevators etc. are not considered here.

In terms of non-RE primary energy ($f_{PEnonRE}$ = 2.3) the range is from about 105 $kWh/(m^2\ a)$ to 200 $kWh/(m^2\ a)$ for the residential and 150 $kWh/(m^2\ a)$ to 190 $kWh/(m^2\ a)$ for the office.

4.4 Humidification and Dehumidification

In cooling dominated climates dehumidification can significantly contribute to the cooling load and demand. Application of energy recovery ventilation can reduce the dehumidification load and demand. In the following Figures, a typical load for an office building in a warm (Rome), moderate (Stuttgart) and cold (Stockholm) climate is shown for the case without mechanical ventilation with heat recovery (MVHR), with heat recovery and with energy recovery (i.e. heat and moisture).

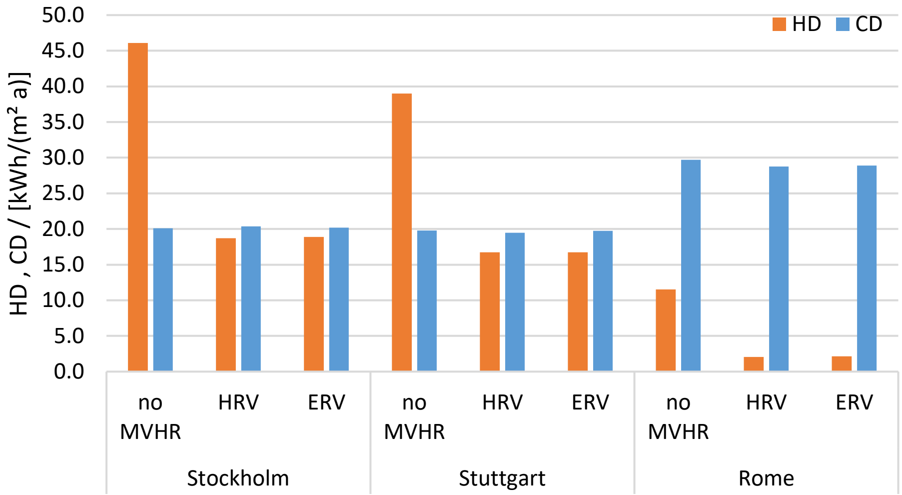


Figure 4-2: Heating Demand (HD) and Cooling Demand (CD) for warm (Rome), moderate (Stuttgart), and cold (Stockholm) climate without MVHR, with HRV and with ERV.

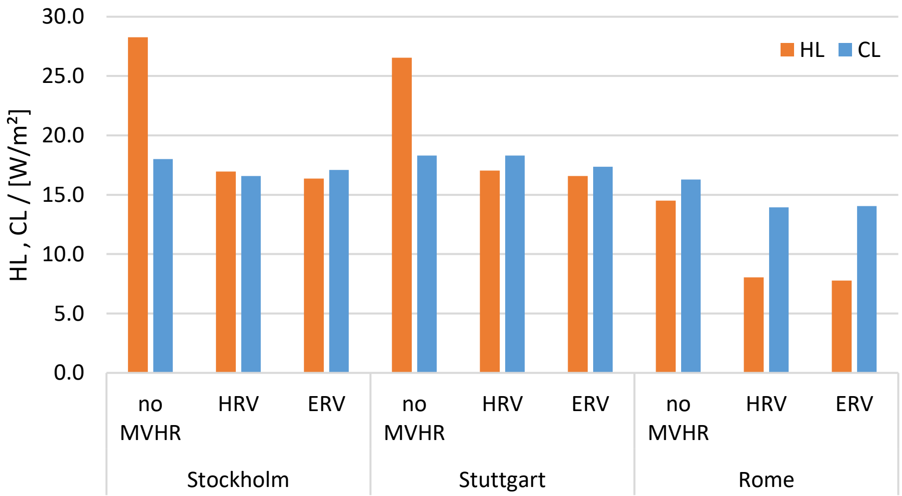


Figure 4-3: Heating Load (HL) and Cooling Load (CL) for warm (Rome), moderate (Stuttgart), and cold (Stockholm) climate without MVHR, with HRV and with ERV.

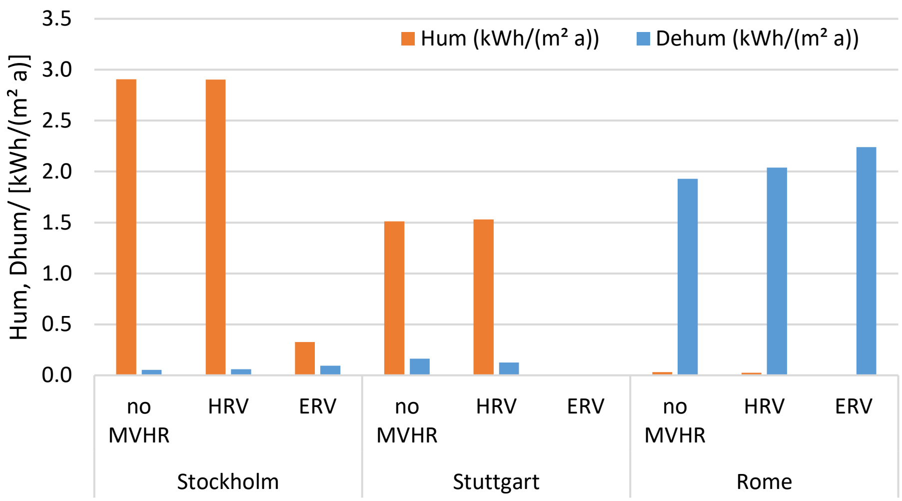


Figure 4-4: Typical Humidification Demand (Hum) and Dehumidification Demand (Dehum) for warm (Rome), moderate (Stuttgart), and cold (Stockholm) climate without MVHR, with HRV and with ERV.

4.5 Heating Demand vs. Heating Load

4.5.1 Office

Figure 4-5 shows the heating demand (HD) vs. the overall heat transfer coefficient with and without MVHR for the three different climates. The heating load is displayed as a function of the heating demand in **Figure 4-5** with and without MVHR. In Stockholm, with MVHR the heating demand can be reduced by approximately 30 kWh/(m² a) and the heating load is reduced by 12 W/m². In Rome, the heating demand can be reduced to zero with MVHR and good envelope quality. Without MVHR the heating demand is a maximum of 10 kWh/(m² a) with a heating load of 14 W/m². A slight increase in cooling demand with increasing envelope quality (lower U-value and lower SHGC) can be recognized. There is no significant influence of MVHR on the cooling demand and cooling as can be seen in **Figure 4-6**. Remark: In all cases, free cooling and MVHR bypass are considered as described in DC.1. Because of the shading control, the cooling load is dominated by the internal gains.

For the case, without MVHR exhaust ventilation is considered with an SFP of 0.2 Wh/m³. It is noteworthy that, particularly in the cold climates (Stockholm and Stuttgart), such ventilation would lead to some discomfort hours (cold air downdraught). For all cases, a const. auxiliary electric load (control) of 20 W is assumed. The electric energy for auxiliary devices and lighting are summarized together with the appliances, here.

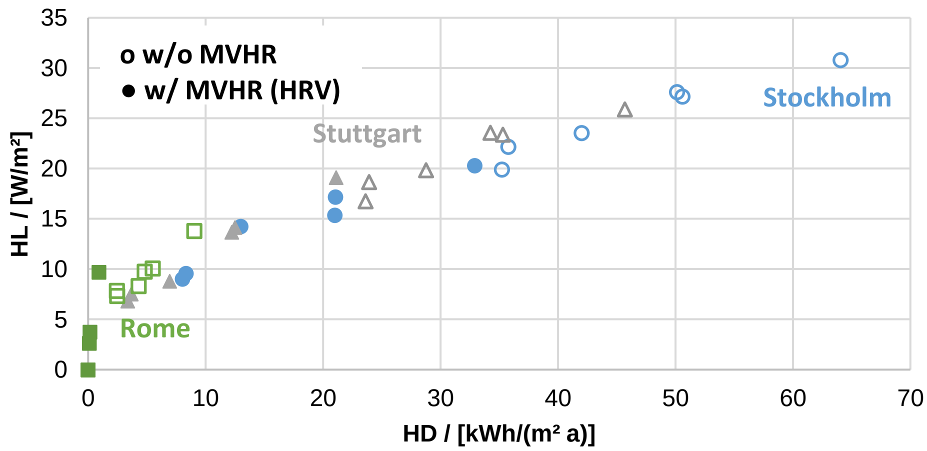


Figure 4-5: Heating Load (HL) vs. Heating Demand (HD) for Rome, Stuttgart and Stockholm with and without MVHR, fluorescent lights.

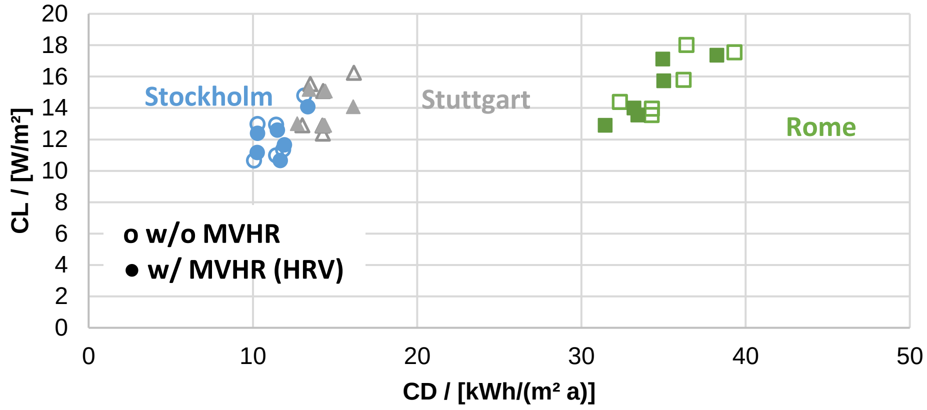


Figure 4-6: Cooling Load (HL) vs. Cooling Demand (HD) for Rome, Stuttgart, and Stockholm with and without MVHR, fluorescent lights.

4.5.2 Residential

In residential buildings (here SFH) the heating load follows a similar trend as in the case of the office cell. It is also of the same order of magnitude as the heating load of the office building. MVHR can significantly reduce energy demand and heating load.

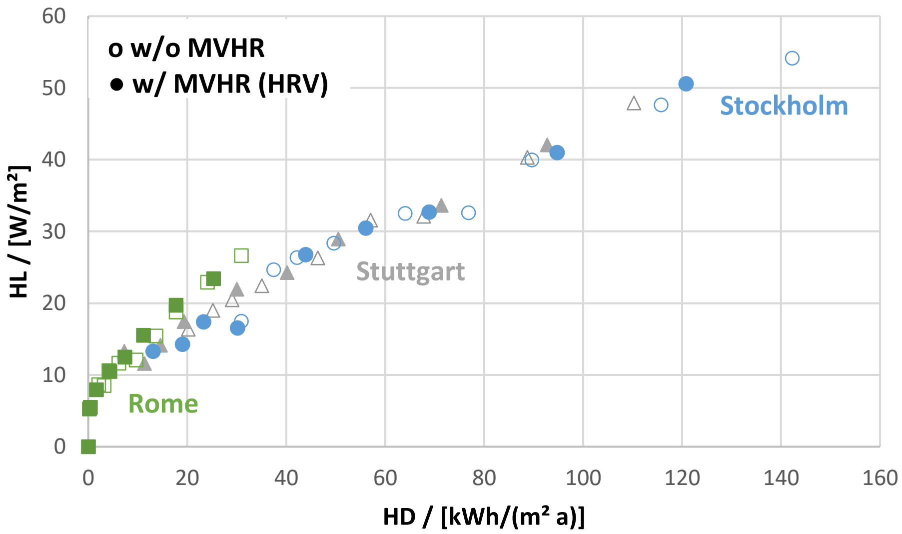


Figure 4-7: Heating Load (HL) vs. Heating Demand (HD) for Rome, Stuttgart, and Stockholm with and without MVHR for the SFH.

4.6 Solar Potential

Based on the simple estimation of the final energy (see above) the maximum possible contribution of (on-site) RE can be estimated for the different building types.

4.6.1 Office

A typical office building with a treated area of 27 m² might have an opaque area of 5.4 m² and for large office buildings, the space on the roof is usually limited. The ratio of the PV area to the treated area is 20% in this case. Even if this façade is faced to the south and is not shaded by e.g., other buildings, the annual yield is with a little bit more than 20 kWh/(m^2_{AT} a) comparably low (FE is between 100 to 150 kWh/(m² a)). So, a high share of the PV can be self-consumed. The supply cover factor is typically in the range of SCF = 70 % for all cases and all climates. The load cover factor varies widely with climate and building electricity demand and ranges from 15 % (Stockholm, poor performance building) to 50 % in Rome (high-performance building).

With PV the non-RE primary energy in an office building can be reduced from about 150 kWh/(m² a) to approx. 100 kWh/(m² a).

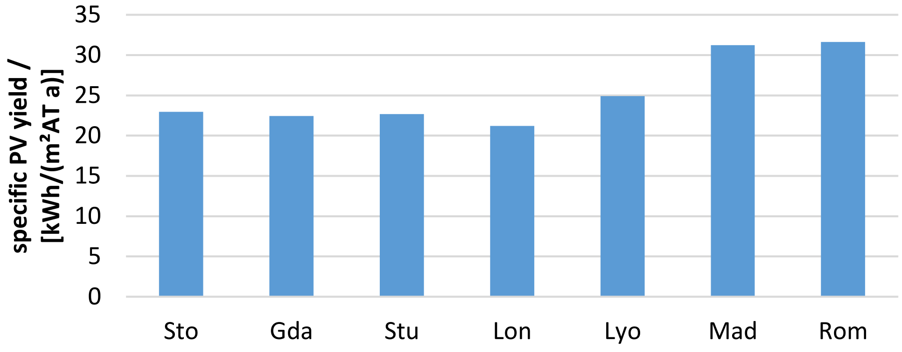


Figure 4-8:Typical annual PV yield related to the treated area of an office cell with 27 m² of the treated area and 5.4 m² of opaque façade area ca. 0.8 kW_p PV.

4.6.2 Residential - SFH

A typical residential SFH with a treated area of 140 m² has space on the roof for a 5 kW_p PV system. The opaque façade is usually large enough to cover another 5 kW_p, but installation is significantly more expensive, and shading has to be considered. As shown above, a high performing SFH in a moderate climate (e.g. Strasbourg) might have a total annual electric energy demand of 45 kWh/(m^2_{AT} a). For the given boundary conditions, with an annual PV yield of 38 kWh/(m^2_{AT} a) for a 5 kW_p PV system on the roof even on an annual basis, the demand cannot be fully covered. With an additional 5 kW_p on the façade, the annual yield would increase (without shading) to approx. 60 kWh/(m^2_{AT} a).

Typical supply cover factor (SCF) in residential buildings (SFH) is in the range of 10% for poor performance buildings to about 4% for high-performance buildings. The SCF is independent of the building quality in the range of 40% (without large additional storage capacities).

With PV the non-RE primary energy of the SFH can be reduced from about 105 kWh/(m² a) to approx. 60 kWh/(m² a).

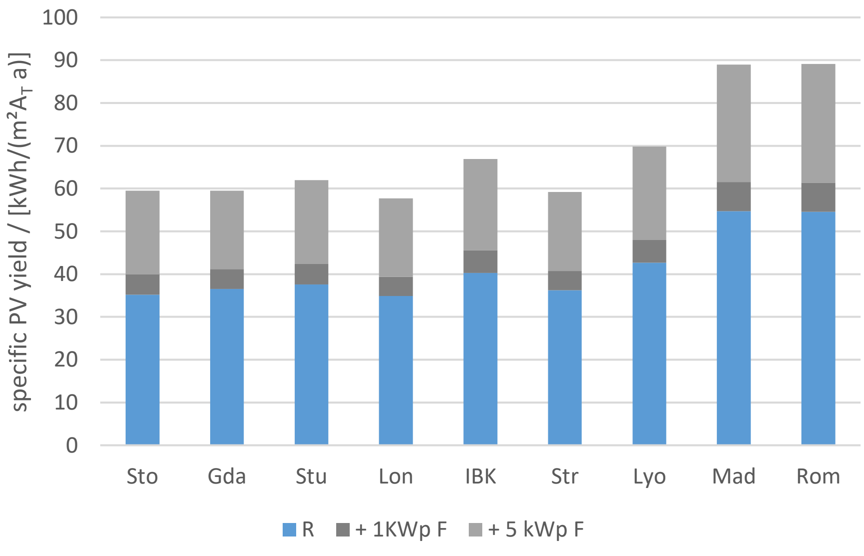


Figure 4-9: Typical annual PV yield related to the treated area of a single-family house (SFH) with 140 m² of treated area and 5 kW_p PV system on the roof (45° south) and optionally additional 1 kW_p or 5 kW_p on the south façade.

4.6.3 Residential - MFH

Size, shape, and number of stories can significantly vary in residential multi-family buildings and with an increasing number of stories, the share of PV on the roof for each flat obviously decreases. In a typical 5-story building, the treated area might be 700 m², the available roof area 80 m² and the opaque façade 115 m² (south faced). The heating demand is typically lower than in SFH (because of the better surface to volume ratio), instead, the DHW demand is typically higher because of higher occupation and more distribution losses.

The ratio of PV area to the treated area is relatively small with 10% without façade and some 30% with façade compared to the SFH (23% without façade and 45% with façade).

Overall, the load cover factor in a high performing MFH with PV on the roof is in the range of 25% to max 30% with a supply cover factor of typically not more than 65%. (SCF can be increased by approx. 10% points with batteries, while the LCF might be increased by about 5%).

5 Building, HVAC and RE simulation

5.1 Modelling and Modelling Approach

Optimal HVAC design is case-specific (type and use of building, location, etc.) and careful system and component design and sizing are recommended. Building and HVAC simulation can help to improve system design and optimal commissioning and operation (i.e. control) of the system.

The broad variety of technologies and system concepts and combinations together with the different levels and scales of this multi-objective optimization problem is a real challenge.

Some aspects, such as indoor air quality, thermal comfort, but in particular visual comfort can only be investigated on a detailed level, i.e. on room or office cell level. Also, some aspects of façade integration require a look into the detail, i.e. the component level (e.g. façade integrated PVT collector coupled to a decentral ventilation unit or heat pump).

Other aspects such as the investigation of the influence of a technology in a building on the grid load require the building and HVAC system level or even the district level (when connected e.g. to the district heating system).

Reference building or benchmark

A common **reference building** is useful to compare different technologies including the influence of different climates. Resulting primary energy consumption of a certain technology and control strategy can be directly compared with those of other solutions. A common reference building needs a detailed description of:

- Geometry (size, glazing ratio, orientation, ground coupling, etc.).
- Building energy standard (envelope quality, air-tightness, etc.).
- Location.
- Usage (occupation profile, internal gains, ventilation, and shading).
- Setpoint temperature.
- Heating (operative temperature).
- Cooling (operative temperature).
- Dehumidification (absolute humidity).
- Ventilation/infiltration:
    - airtightness and window ventilation;
    - mechanical ventilation rate/heat recovery effectiveness;
    - night ventilation (volume flow and control settings and setpoints).
- Shading (reduction factor and control settings and setpoints).

An **individual building** with the **reference system** serves as a **benchmark** in the case of residential buildings. The solar envelope solutions are compared against this benchmark in terms of energy performance and primary energy consumption. Maintaining thermal comfort and indoor air quality has to be proven for each solution and it is a prerequisite.

Zoning

Building models and modelling approaches have to consider the different scales and appropriate thermal zoning is key to accurately predict the performance of a technology on building level and, at the same time, allow investigating the influence on the comfort, or controlling to maintain the building within the comfort range and required IAQ.

In particular, the investigation of daylighting and glare, which needs zoning on room level and also to consider the interdependencies with the HVAC system of a building at the same time is a challenging task.

A 1-zone model of a building is usually sufficient to predict accurately the heating and cooling demand of a building. Predicting the influence of different use, function, and schedule of zones, orientations, locations (internal/perimeter, top/centre/bottom), etc. is not possible. Furthermore, correctly predicting thermal capacity and moisture buffer of the building is a limit.

A 1-zone model of a cell (or a flat or a room in a MFH) is simple to develop and fast but does not allow to model a central HVAC system, nor interaction with the electricity grid.

Multi-zone models are complex, require a lot of information that might not be available during the planning phase of the building, and feature long simulation times.

Extrapolation of the energy demand (heating/cooling) from an office cell (or a flat) to the entire building is limited to simple geometries and error prone. Contrariwise, the prediction of thermal and visual comfort based on a single-zone building is also not possible. Hence, in order to accurately predict both with one model, either very complex models are required, or uncertainties have to be accepted.

Cell to Building

There exist some approaches to extrapolate from cell to the building, but further work is required.

5.2 Workflow

In Subtask C of IEA SHC T56 the following methodology was developed and implemented:

- Simulation (or calculation or monitoring) based assessment of the building (e.g. office cell, office building, flat, or building).
- Determination of monthly energy demand (Useful Energy UE):
  - Heating Demand,
  - Cooling Demand,
  - DHW Demand,
  - Auxiliary Energy Demand,
  - Lighting Demand, and
  - Appliances.
- Evaluation of HVAC System Performance (e.g. Heat Pump, Solar Heat Pump, etc.).
- Determination of Electric Energy Demand (Final Energy).
- (onsite) RE generation (PV), analysis on time step level, at least monthly:
  - LCF.
  - SCF.
- Monthly Electric Energy Consumption.
- Electric Energy Balance -> Monthly Purchased (electric) Energy (Grid Load).
- Electricity Mix (Fossil, Nuclear, RE), monthly non-RE PE conversion factors
  -> non-RE Primary Energy Demand / Primary Energy Savings (with respect to reference).
- Economic analysis (costs per saved kWh_{PE} based on LCC).

5.3 Key Performance Indicators (KPIs)

In order to compare results from different simulation platforms, KPIs may be used. Key Performance Indicators (KPIs) useful for the evaluation of the simulation results are here summed up.

- Environmental analysis:

  1. Non-Renewable Primary Energy (PE);
  2. Primary energy savings: $\Delta PE = PE - PE_{ref}$;
  3. CO2-emissions;
  4. CO2-emissions savings: $\Delta CO2 = CO2 - CO2_{ref}$.

  Both Primary Energy and CO_2-emissions depend on Useful Energy (UE) and Final Energy (FE):

5. Seasonal Performance Factor (SPF): $SPF_j = \frac{Q_j}{FE_j}$;
6. Primary Energy Ratio (PER): $PER_j = \frac{Q_j}{PE_j}$;
7. Solar Fraction (SF): $SF_j = \frac{Q_{SF,j}}{Q_j}$.

- Thermal comfort:
  1. Predicted Mean Vote (PMV) and Predicted Percent of Dissatisfied people (PPD);
  2. Operative temperature (ϑ_{op});
  3. relative humidity (rH);
  4. Overheating period (τ_{OH}).

- Integration of Renewable and Storage:
  1. self-consumption (SC);
  2. Load Cover Factor (LCF): $LCF = \frac{SC}{E_{tot}}$;
  3. self-production (SP);
  4. Supply Cover Factor (SCF): $SCF = \frac{SP}{PV}$;
  5. The solar yield (SY);
  6. The solar fraction: $SF = 1 - \frac{Q_{BU}}{Q_{tot}}$;
  7. The solar efficiency (SE) (see section 3.4).

- Indoor air quality:
  1. Humidity;
  2. CO_2 concentration.

- Visual Comfort:
  1. (Continuous) Daylight Autonomy cDA;
  2. Luminance threshold Lmax;
  3. Daylight Glare Probability;
  4. Daylight Glare Probability simplified DGPs;
  5. Spatial Daylight Autonomy sDA;

5.4 Platform

As reported in DC.1 and DC.2, different tools have been used for the calculation/simulation of the reference office cell (shown in **Figure 5-1)**. The validated models will be published and freely available on the IEA SHC Task56 web platform. Together with the models, a factsheet will be provided reporting a short description of how the models can be used.

Here below a short introduction of each tool/software is reported:

- EnergyPlus™ v8.5 is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption for heating, cooling, ventilation, lighting, and plug and process loads and water use in buildings [2].

- TRNSYS 2018 (TRN) is a transient system simulation program based on a component approach with a modular structure. The TRNSYS library includes a detailed multizone building model and components for HVAC systems, renewable energy systems, etc. [3].
- Simulink carnotUIBK v2.1 (SIM_IBK) is a Matlab/Simulink library, compatible with CARNOT Toolbox, developed by the University of Innsbruck, based on object-oriented programming of a parameterized building model [4].
- Simulink ALMAbuild v 2.2 (SIM_BO) is a Matlab/Simulink library, compatible with CARNOT Toolbox, developed by the University of Bologna where a user develops a building model by means of a series of Graphical User Interfaces [5].
- MODELICA (MOD) is a non-proprietary, object-oriented, equation-based language to conveniently model complex physical systems, with a wide open-source library (in this case the LBNL Buildings library is used) [6].
- DALEC (DAL) is a free web tool developed by Bartenbach, University of Innsbruck, and Zumtobel. The main focus is on combined thermal and lighting building simulations in early design phases [7].
- FENER (FEN) is a web-based platform for Integrated daylight, glare, and energy evaluation of fenestration technologies [8].
- PHPP v 9.1 Passive House Planning Package is a quasi-steady-state calculation tool, developed as a spreadsheet, for the use of architects and planning experts [9].

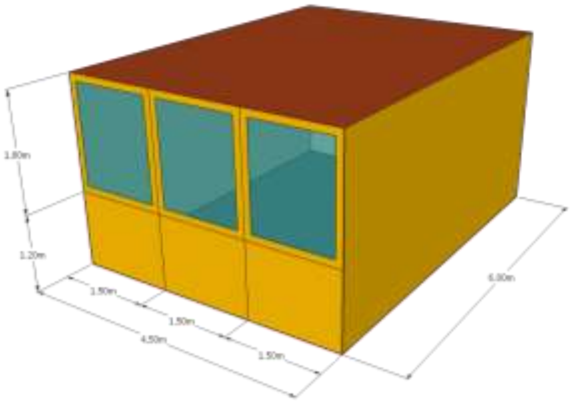


Figure 5-1: View of the reference office building.

5.4.1 Platform modelling features

Crawley et al. in [10], created a report envisioned as a community resource that has to be regularly updated and expanded as the tools mature and grow. Starting from this idea and based on the experience gained during the modelling process of the reference office building using different simulation/calculation platforms, the authors decided to report the main pros and cons of each tool (see **Table 5-1**).

Table 5-1 is divided into four main sections reporting information regarding:

- Input/Output management;
- Available models and features;
- Support to the user;
- Cost of the platform.

Table 5-1: Main features of each tool. For each section different points are tackled and the "evaluation" of each tool for each point is given with an answer that might be true, mostly true, neutral, mostly false and false.

		TRUE							MOSTLY TRUE							NEUTRAL							MOSTLY FALSE							FALSE						
		EP	TRN	SIM IBK	SIM BD	DAL	MOD	PHPP	EP	TRN	SIM IBK	SIM BD	DAL	MOD	PHPP	EP	TRN	SIM IBK	SIM BD	DAL	MOD	PHPP	EP	TRN	SIM IBK	SIM BD	DAL	MOD	PHPP	EP	TRN	SIM IBK	SIM BD	DAL	MOD	PHPP
INPUT/OUTPUT	Graphical user interfaces (GUI) are (freely) available or included in the library	●	●	●	●	●	●	●																												
	All features of the provided input files can be imported directly in these GUIs		●		●	●	●	●								●									●											
	Console-based interface requires user expertise	●		●						●		●		●								●					●									
	Compatibility with different input data formats and user-defined output data			●	●				●	●				●																				●		●
	Simple input [1]					●		●								●	●	●			●					●										
	Easy to learn					●									●		●						●		●	●		●								
	Import of geometry from SketchUp or other 3D design tools (gbXML)	●	●	●	●																●													●		●
	Data import from Excel and PHPP [2]			●																										●	●		●	●	●	●
	Standardized post-processing [3]										●		●		●								●	●				●					●			
MODELS AND FEATURES	Dynamic multi-zone simulation	●	●	●	●		●																											●		●
	Detailed models available for shortwave and longwave radiation distribution	●	●		●		●																									●		●		●
	Evaluation of Daylight comfort	●				●											●															●	●		●	●
	Availability of simplified and detailed models for construction elements and thermal zone [4]			●			●			●		●																		●				●		●
	Simulation of the 3D spatial distribution of the convective temperature [5]						●		●	●		●																				●		●		●
	Simulation of the 3D spatial distribution of the radiative temperature		●						●			●									●											●		●		●
	Analysis of indoor thermal comfort indexes	●	●		●		●																									●		●		●
	Hygrothermal model for the opaque structures [6]	●		●																				●									●	●	●	●
	High potential for customization of control strategies and HVAC system layouts			●	●		●			●						●																		●		●
	Co simulation with other tools [7]								●	●	●	●		●																				●		●
SUPPORT	Available documentation	●	●			●	●															●			●	●										
	A large user-base and active support from the online community	●	●											●															●			●	●	●		
	Wide range of example models are available	●	●				●																		●	●	●		●							
	Large variety of detailed and simple subsystem models are available	●	●				●				●	●																						●		●
TIME STEP	Maximum time step can be selected by the user	●	●	●	●																													●	●	●
	Possibility to use a variable time step during the simulation [8]			●	●		●		●																						●			●		●
	Short calculation times [9]					●		●																						●	●	●	●		●	
COST	Freely available library and software on which the library works [10]	●				●															●								●		●	●	●			

Some points need further clarifications which are here reported:

- [1]Simple Input: Some tools require a high degree of detail in the inputs. As an example in Simulink UNIBO only the R-C model of the opaque structures and complex fenestration model are available at the moment, therefore the user must know the specific properties of each layer of the opaque structures and the optical properties of the window. However thanks to the available GUI the user is guided through the input of data;

- [2]Data import from Excel and PHPP: In SIM IBK it is possible to import all the building inputs from the predefined Excel sheet or PHPP. Some other tools might be able to read data from Excel format but they cannot read all the building data in a structured way;

- [3]Standardized Post-processing: in SIM IBK, PHPP and DAL standard output plot can be automatically created without any additional plug-in or programming effort;

- [4]Availability of simplified and detailed models for construction elements and thermal zone: Some tools offer different models from simplified (e.g. 1-star node for the thermal zone and UA for construction elements) to detailed (e.g. 2-star node for the thermal zone and RC or complex fenestration system for construction elements) while other tools have the availability of either only complex or only simplified model;

- [5]Simulation of the 3D spatial distribution of the convective temperature: this is a feature that bridges the world of CFD simulation with the world of dynamic building simulation. Some tools such as MOD (using a specific library FFD thermal zone model), TRN, SIM BO are able to simulate with different degree of detail a 3D distribution of the convective temperature in the thermal zone;

- [6]Hygrothermal model for the opaque structures: A lumped moisture buffer model is included in TRN but the moisture absorption is not considered for each wall, while in SIM IBK the moisture transfer could be modeled n each structure. Other tools disregard the humidity balance;

- [7]Co-simulation: FMI can be considered a robust and efficient way that is widely supported for co-simulation and Modelica offers high capabilities;

- [8]Possibility to use a variable time step during the simulation: this feature regards the timing with which the equations of the model are solved. If this feature is available the software itself decide when it is necessary to solve the equations based on the behavior of the main variables;

- [9]Short calculation times: DAL and PHPP can be considered instantaneous therefore assuming this as a reference all the other dynamic simulation tools require much longer simulation time. Note that DAL and PHPP adopt simpler models than the other dynamic simulation tools;

- [10]Freely available library and software on which the library works: DAL and EP are completely freely available while the other tools require to buy a license (e.g. Matlab for both SIM IBK and SIM BO, TRNSYS, and Dymola). Anyhow it must be noticed that for Trnsys a free limited version is available and for Modelica free open source environments are available.

5.4.2 Predesign Tools vs Detailed Design Tools

The construction of a new building or a deep renovation passes through several phases. In each phase of the project, the user has different needs. Usually, in the preliminary planning, different solutions are investigated and compared disregarding the details. In this first step, detailed data are typically not available, and predesign tools which are able to provide results quickly are preferable.

Once the best solution or a restricted set of solutions (for the building envelope and HVAC) has been decided, they can be investigated in detail and optimized. In order to analyse the details of the interaction between the building and the HVAC components, it is required a tool that can predict the dynamic behaviour of the studied system.

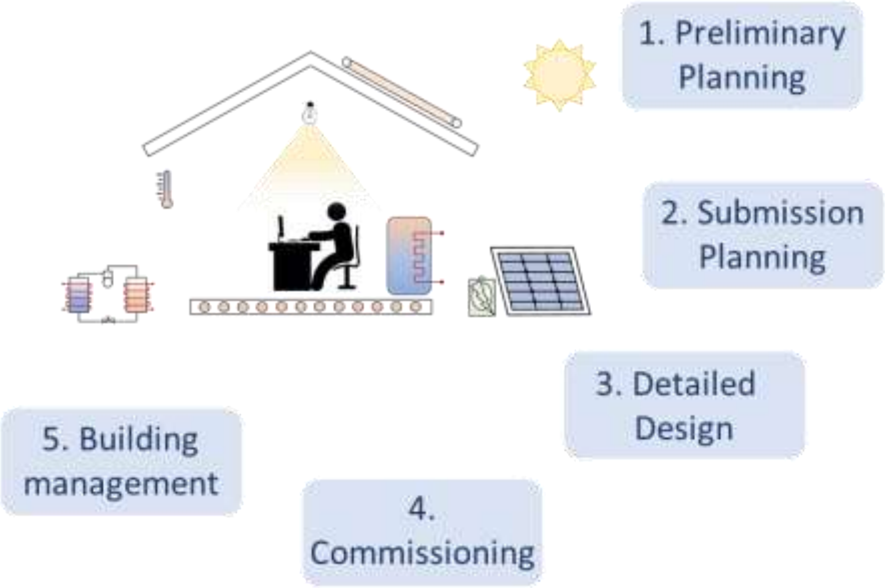


Figure 5-2: Building design phases.

In the framework of the IEA SHC Task 56, predesign tools (i.e. PHPP), specific pre-design simulation tools (i.e. DALEC or Fener), and design tools (i.e. Matlab/Simulink, EnergyPlus, Modelica and TRNSYS) have been used and the results compared against each other.

5.4.3 Monitoring

In the case of monitoring (Demo Buildings), there is usually also the need for normalizing the energy demands with respect to:

- Climate (ambient temperature, solar radiation);
- User Behaviour;
- Indoor temperature (setpoint);
- Occupation (internal gains);
- Ventilation;
- Shading;
- DHW demand;
- etc.

Building, HVAC, and RE Simulation can support this process.

5.5 Multi-Objective Optimization and Cost-optimality

The mechanisms and dependencies within buildings and buildings within district energy systems are very complex. Occupancy profiles, equipment consumption profiles, and internal gains (related to these profiles) have to be considered. In order to allow the simulation-based analysis for design and operation optimization, numerical simulation models of different levels and scales are required. The models include buildings with their local energy system for heating, cooling and domestic hot water preparation, thermal networks as well as optionally energy production and storage (local and/or central). Due to the multi-objective nature as well as because of the complex interaction of the components of the system as a whole, to find the best solutions, it is required to start from the detail and evaluate the manifold possible combinations on building or district level.

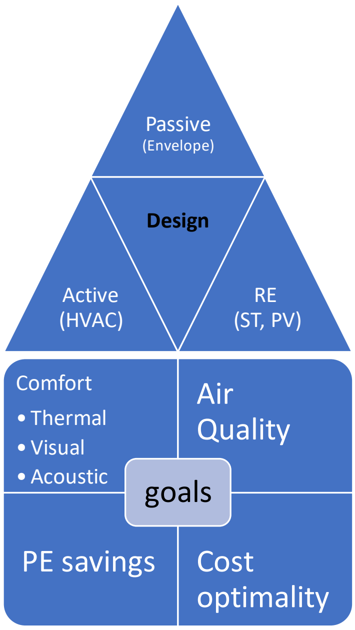


Figure 5-3: Scheme of a multi-objective optimization – building, HVAC, and RE.

Example

The investment costs increase with the thickness of the insulation and/or area of PV or ST. The FE and energy costs decrease with thickness or area, respectively. Hence, the (mathematical) optimum of the annual capitalized total costs can be determined at rel. thickness, rel. area of 0.42 (example!). The minimum is relatively flat and with little extra costs, significantly higher savings can be obtained.

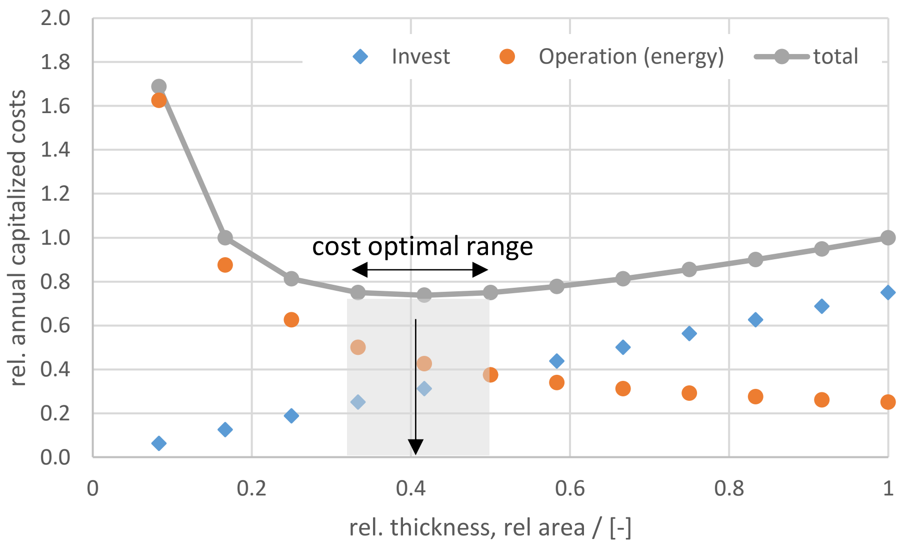


Figure 5-4: Example of Cost-Optimal Solution.

6 Design of Daylighting Systems

Effective utilisation of daylight in office buildings is an essential design consideration for improving the well-being, health, and productivity of office workers ([11] [12] [13] [14]). Additionally, daylight utilisation can significantly reduce a building's energy consumption ([12] [13] [14] [15]). Solar active building envelopes that focus on harvesting daylight can be instrumental for reaching these goals, but their successful application is more complex than a mere technological switch [14] and [16]. During the development, application and control of façade integrated daylighting systems, the competing performance aspects of daylight provision, visual and thermal comfort, costs and energy performance (including energy harvesting) need to be balanced ([12], [14], [16], [17], [18]). The new standard EN 17037 "Daylight in Buildings" offers designers recommendations for adequate daylight design, addressing the aspects of daylight provision, exposure to sunlight, view to the outside, and glare protection [19].

6.1 Multi-objective balancing for a proper daylight design

The task of balancing the positive effects of admitting solar energy (more daylight and view to the outside, reduced lighting, and heating energy consumption) with its negative effects (visual discomfort through glare, increased cooling energy consumption) is complicated by the fact that building energy performance is increasingly determined by interactions between the thermal and the visual domain. The traditional approach in the building industry for designing facades has been to treat these two physical domains as separate design and engineering problems. However, with the advent of increased daylight utilization, high reflectance metal coatings, and advanced solar shading controls, these domains are becoming increasingly interlinked. The two case studies on daylighting systems and enhanced artificial light control presented in DC.2 (see 2.2.4 and 2.2.5) point out these interactions and give recommendations for proper balancing.

Several interacting design features can be leveraged to improve the effects of façade integrated daylighting technologies on whole-building performance. Traditionally, these features are designed by different decisionmakers at different moments in the life cycle of a building. Façade system developers can improve the performance of façade integrated daylighting technologies through the design (geometry) of their products and the specification of the materials (physical properties) that they use. For dynamic façade systems, also control aspects (control rules, thresholds, and sensors) can be leveraged to improve the overall performance. Additionally, building designers can use building-related design aspects (dimensioning of windows, glazing, and other façade features) as optimization parameters. The combination of façade integrated daylighting product, control approach and the overall building should be considered as an integrated system. Improving the performance of façade integrated daylighting technologies, therefore, requires a holistic approach that addresses all these design and control aspects in an integrated manner [20, 21]. Special emphasis should be placed on the evaluation of visual comfort conditions. Deliverable DC.2 section 2.1 describes two simulation frameworks that were developed specifically for such applications.

6.2 User interaction and the role of occupants

Pleasantly managing daylight utilization becomes more challenging due to the need to appropriately address the role of occupants, their individual habits, and personal preferences. Hence, occupants request active control of façade integrated daylighting and shading devices as it allows them to address their personal visual comfort conditions [22, 14, 23, 24, 25]. Traditionally, the provision of measures to prevent glare discomfort is not treated as an integral part of the building design process and is often considered as the responsibility of the building's tenant. As it is illustrated in the case studies presented in DC.2 (see 2.1.4.3, 2.2.4 and 2.2.5) the manner in which glare discomfort is addressed has a very strong influence on the other façade performance aspects and it is recommended to consider preventing visual discomfort as an essential goal in the façade design process.

6.3 Wellbeing, health, and productivity

In improving the visual indoor environment, façade integrated daylighting systems can contribute to the well-being, health, and productivity of office workers. Historically, standards and interior lighting design practices were only based on visual needs (i.e. to perform visual tasks) but did not include recommendations for lighting designs to trigger non-visual effects on human beings. In the last years, scientific research increased efforts to explore the non-visual effects of light. As a matter of fact, it was proven that circadian entrainment is influenced by the timing, intensity, duration, and wavelength of light exposure and depends on the light exposure history [26, 27, 28, 29]. Although several models and metrics were developed and standards published in recent years [30, 31, 32], there is no scientifically-based consensus for the appropriate minimum light exposure threshold to effective circadian lighting or for how long the exposure duration must be. The knowledge on biological effects of light is based on limited data, mainly from studies conducted during the night under highly controlled laboratory conditions and in disciplines of neuroscience and photobiology. Translating results from these studies into useful metrics and figures for lighting designers is of growing interest in order to provide guidance by developing applicable guidelines for circadian lighting design.

Methods for evaluating the circadian effectivity of daylighting technologies are becoming available [29, 33, 34, 35] which allow designers to analyse the spectrum, timing, intensity, and duration of occupant's light exposure in relation to objectives related to a healthy circadian entrainment. As such methods are likely to become more reliable and widely available soon, it is recommended to integrate these evaluation methods in the design process of solar active façades.

6.4 View to outside

The degree of visual connection to the outdoors has been linked to the well-being and productivity of occupants. Although research in this field has not led to any universally agreed-upon design guidelines or metrics [13] there is sufficient evidence that view content, view clarity, and view quantity and proportions are factors of importance [36, 37, 38, 39, 40]. It is recommended that these factors are considered in the design process and several workflows have recently been proposed for supporting such considerations [41, 42, 43, 44, 45, 46, 47].

6.5 Economic aspects and ROI

Although there is sufficient research indicating the importance of visual comfort, exposure to daylight and views for improving the health, well-being, and productivity of occupants, these findings cannot be translated into quantifiable financial benefits or avoided costs from specific daylighting technologies [11, 13, 37, 48, 49].

Case study 1.2.4 showed that, even when making modest assumptions regarding the increased economic output of office workers, the financial benefits of increased visual comfort is of a larger order of magnitude than the financial benefits or drawbacks that daylighting technologies might have in terms of their energy-saving and HVAC sizing effects. In the design of solar active facades, it is therefore recommended to place a strong emphasis on daylighting and visual comfort performance.

With regard to energy performance, the trade-offs in balancing the undesired effects of the admission of solar energy with its positive effects are strongly dependent on the efficiency of cooling energy equipment and the generation of electricity. Case study 1.2.4 showed that design decisions can be influenced strongly by different assumptions regarding these efficiencies.

The increasing penetration of renewables is likely going to change the characteristics of electricity grids and high-efficiency cooling solutions are likely to be applied more often in the near future. Considering that such changes are likely to occur within the expected lifetime of a building it is recommended that designers consider plausible, and preferably multiple scenarios, for such assumptions and choose design solutions that are robust to such changes.

7 Summary of case studies

7.1 Overview of buildings and applications investigated within the IEA SHC Task 56

Table 7-1 gives an overview of case-studies investigated within IEA SHC Task 56. Detailed results are reported in D.C2. In the following the results are summarized in part A for non-residential (i.e. office) and in part B for residential buildings.

Table 7-1: Overview of case-studies (S: simulation, D: demo).

		new				renovation			
		residential		tertiary		residential		tertiary	
		SFH	MFH	office	other	SFH	MFH	office	Other
Focus	cost-effective	S	S, D	S		S	S	S	
	high performance (e.g. NZEB)	S	S	S	D	S	S	S	
Application	Ventilation (HRV/ERV)	X	X	X	D	X	X	X	
	Heating	X	X	X	X	X	X	X	
	Cooling/Dehumidification			X				X	
	Air-conditioning			X	X			X	
	DHW	X	X			X	X		
	Lighting/shading/glare prot.			X				X	
	Electricity	X	X	X	X	X	X	X	
RE	(BI)ST			X	X				
	(BI)PV	X	X	X	X	X	X	X	
	(BI)PVT			X				X	
	HP	X	X	X	X	X	X	X	
	Other (e.g. SDWR)	X	X			X	X		
Evaluation	Efficiency	X	X	X	X	X	X	X	
	IAQ	X	X	X	X	X	X	X	
	thermal comfort	X	X	X	X	X	X	X	
	visual comfort/glare			X	X			X	
	Environmental (PE, CO_2)	X	X	X		X	X	X	
	LCA								
	LCC	X	X	X	X	X	X	X	

7.2 Part A: Office Building

7.2.1 Cost-optimality - Variation of the Envelope and HVAC Quality and BIPV

This study compares the performance (in terms of cost vs. primary energy or cost difference vs. primary energy savings) and cost-optimality (in terms of cost per saved kWh of primary energy vs. primary energy savings) for the office cell in three climates by varying the envelope as well as HVAC quality and considering or not the PV. Completely different results are obtained whether heating or cooling dominated climates are considered. In Rome, the envelope quality is not very sensitive to the overall building performance. Thanks to the installation of a (BI)PV system the grid electricity demand can be reduced to approximately 67% with fluorescent light and to approximately 50% with LED. On the other hand, in the cold climates, a good envelope is the key in order to achieve good building performance. Moreover, the implementation of a heat pump appears to be beneficial. In all climates, the use of LED instead of fluorescent light is recommended with all systems' combinations.

Results show that under the given boundary conditions, (BI)PV is not economic, neither in the cooling nor in the heating-dominated climates. Contrariwise, PV is required to reduce the primary energy demand to acceptable values. From this study, it can be concluded that on the European level, it is recommended to foster the improvement of the envelope and the use of heat pumps in central/northern climates and to subsidise the use of PV in southern climates.

7.2.2 Analysis of the impact of different HVAC configurations and control strategies on primary energy and cost savings for an office building

In order to mitigate climate change, sustainable and responsible use of resources is required. In the present study, different technologies applicable to the renovation of an office building are evaluated considering both economic feasibility and environmental impact for the climates of Rome, Stuttgart, and Stockholm. Decentralized heating and cooling systems represented by different types of heat pumps (i.e. air-to-air On/Off and modulating) are considered in combination with photovoltaic panels (PV), battery, and efficient lighting (LED) in order to investigate the achievable energy savings and the additional cost. The environmental impact is evaluated in terms of electricity and total primary energy (PE) savings calculated with constant and monthly conversion factors representing different scenarios with different share of renewables in the electricity mix.

It was observed that the energy savings calculation method influences the ranking of renovation packages. High-energy savings with low additional cost are achievable with HP in combination or not with LED and PV, in Stockholm and Stuttgart, and with LED and PV in combination with electric heating in Rome. Battery brings additional energy savings with high additional costs.

7.2.3 Integration of the PV-Modules into the Building Skin (BIPV/T Concept)

Building-integrated PV systems (BIPV) are being considered as active façade elements in modern buildings. Usually, the main purpose is electricity generation. However, synergies could be achieved if such a building-envelope component is regarded as a BIPV/T element. In this research work, the office building adopted in the IEA SHC Task56 was investigated as a case study for such a scenario. The PV-Façade modules installed at the south-oriented external wall of the office building were thermally coupled and modelled using the glazed BIPV component (Type567) offered in the TESS electrical library within the dynamic simulation environment TRNSYS18. A couple of implementation methods were revised to practically benefit from the possible thermal utilization of the BIPV/T concept. Direct ventilation was chosen as a first application method for the thermal part of the BIPVT system. A fan-based mechanical system with a simple control strategy was considered for that purpose.

For sensitivity analysis and also to benchmark the proposed BIPV/T system, three simulation cases were considered. The first case adopts the operation of the fan of the BIPV/T system according to the control strategy. The second case implies a forced shut-off of the BIPV/T mechanical system, i.e. same as case (1) but there is no forced airflow in the ducts of the BIPV/T system. Finally, the third simulation case does not include a BIPV/T component, only PV-Modules. This latter is considered as the reference case where no thermal coupling between the PV-Modules and the building external walls is accounted for. The first simulation results could be achieved to assess the added value of such systems to the thermal energy demand of the building. From the thermal perspective, it could be concluded that integrating a PV-Layer to the building envelope, as configured in this case-study, is beneficial all over the year. In case (2), the transmission losses are reduced in winter while increased in summer, in comparison to the reference case. Such behaviour matches well the thermal energy demand of the building, which eventually helps the yearly energy consumption. However, implementing a mechanical (fan) system to the BIPV/T system (case 1) should be carefully considered. It is unconditionally beneficial in summer (even more beneficial than the humble numbers of case (2) thanks to the cooling effect). However, to be beneficial in winter, the preheated air should be re-used within the building's ventilation system. Nevertheless, the control strategy has to be more sophisticated than the one presented in this study in order to avoid any overheating which may lead to an undesired cooling demand during wintertime. On the other hand, and from the electrical perspective, cooling down the PV-Panels is beneficial in general. In case (1), the PV-Temperatures were less, the PV-Efficiency was improved, and hence the electrical power was higher, in comparison to case (2). Such a benefit was at the highest levels in moderate climates, represented by Stuttgart. The annual increase in the PV-Power generation was 2.31%, compared to 1.74% in Stockholm and 1.62% in Rome. However, it was not possible to benchmark the results of the BIPV/T cases (cases 1 and 2) to the reference case (case 3). Comparing the electrical power produced by a BIPV/T model in TRNSYS to that produced by only a PV model is an inaccurate method and should not be done till advanced conditioning to the modelling components is carefully considered after being tested.

7.2.4 Integration of solar thermal collectors in curtain walls in a tertiary office building: simulation-based evaluation of the energy performance

The energy performance of solar thermal collectors integrated into the façade of an office building is assessed. The solar thermal collectors enable to convert the solar radiation into heat used to cover a share of the space heating and hot water preparation heat demands of the building. The assessment is carried out by means of dynamic energy simulation (TRNSYS) for a few locations (Rome, Stuttgart, and Stockholm) and different orientations of the solar façade and configurations of the building's floors. Results show that the heat transfer between the thermal collector and occupied space is not significant due to the high insulation levels of the parapet. Overall, it is possible to reach interesting reductions in the use of fossil-sourced heat generators up to 20% in Stockholm, 29% in Stuttgart, and 67% in Rome, with better performances for larger and south-oriented solar facades. The size of the solar water storage varied between 40 to 70 l/m^2 of collector enables to achieve only limited performance improvements.

7.2.5 Solar thermal Venetian blind as synergetic and adaptive sun protection device in double skin façades

Solar thermal Venetian blinds (STVB) offer a novel solution to reduce the energy demand of buildings with highly transparent façades as described in DC.2. They can provide solar control functions like adaptive glare protection, control of solar heat gains, and daylight. At the same time, the STVB functions as a solar thermal collector and can be used to preheat domestic hot water or as a source for heat pumps. STVB can be integrated into glass facades such as double skin and closed cavity façades and prevent overheating of the cavity by extracting excess heat.

The simulations study the effect of this transparent solar thermal collector on passive solar heat gains (via the transmission of solar radiation and secondary heat gains), on solar thermal yields (i.e. the collector functionality) as well as daylighting (part of the solar control functionality). These effects are studied in yearly building performance simulations. First, preliminary results showed that the STVB can lower the cooling demands compared to a similar façade with conventional Venetian blind. The reduction of the solar heat gain coefficient can be an interesting feature of the STVB, potentially improving fully glazed facades by preventing overheating of the interior in summer as required by energy efficiency and building codes. The simulation studies will be continued within the research project "DESTINI" funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) which will start in May 2020. Within this project, the STVB is planned to be realized within a real building project and monitoring will be conducted to validate the simulation results.

7.2.6 Kindow sun-tracking vertical blinds

Different façade solutions each come with different investments, operational costs, and benefits. In designing facades and selecting glazing and solar shading systems, the competing performance aspects of visual comfort, daylighting performance, thermal comfort, costs, and energy performance will, therefore, need to be balanced. In this case study, the performance of an advanced indoor solar shading system (the Kindow sun-tracking vertical blind system) is assessed in relation to other conventional solutions for controlling the admission of solar heat gains and daylight. This study illustrates how simulations can be used to find balanced trade-off solutions considering the multitude of conflicting performance aspects in the selection of solar shading and glazing technologies. The influence of different assumptions regarding the efficiency of cooling systems and the primary energy ratio (PER) of electricity on energy performance and total costs are evaluated in order to explore how the design space can evolve as a result of changes in the technical and economic context. The results of this study show that the advanced Kindow solar shading concept offers superior daylighting, visual comfort, and energy performance compared to conventional automated solar shading solutions, similar to lower total building-related costs. This study concludes that reducing solar heat gains will become less important in the selection of glazing and the control of solar shading systems when daylight dimming systems and more efficient cooling systems become more ubiquitous, and the presence of renewable electricity from PV gives rise to a favourable PER in the summer months. Additionally, it is illustrated that for daylighting technologies, the financial benefits of an improved visual environment are likely to be large in comparison to differences in terms of other operational costs.

7.2.7 Impact of Integral Day- and Artificial Lighting Solutions on Energy Demand and User Comfort

Integral control strategies for day- and artificial lighting play a crucial role in enabling a high level of visual and thermal comfort to the occupants while reducing the energy demand for heating, cooling, and lighting. Within this study, the potential in energy-saving and user comfort is evaluated for different shading- and enhanced daylight redirecting façade systems in combination with a dimmable, daylight-responsive artificial lighting. Besides energy demand, the requirements for visual comfort by daylight availability and glare protection are evaluated for each case. This study, elaborated within IEA SHC Task 56 – Building Integrated Solar Envelope Systems for HVAC and Lighting, represents a typical office setup with a south-oriented façade and includes a comparative evaluation for the different locations of Stockholm, Stuttgart, and Rome.

Within IEA SHC Task 56, different “Solar Envelope” solutions for offices and residential buildings have been investigated and evaluated by means of building and system simulation. To achieve an optimal facade integration by partly contradicting technologies including HVAC, Renewables, and Lighting, control optimization of those systems was one of the major goals to propose a strategy for a successful solution. As a prerequisite, thermal and visual comfort must be proven for each solution. Furthermore, there was a clear need to understand the influence of a proper daylighting strategy on the resulting heating and cooling demands and loads. While the former allows reducing operating costs over the lifetime, second might allow to optimize the HVAC sizing and therefore to reduce investment costs, which might be an additional driver for innovative daylighting solutions in the future.

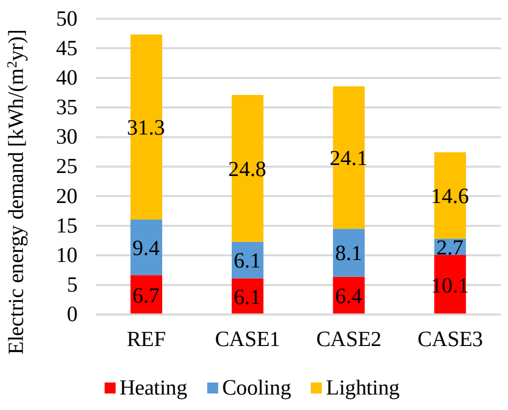
As test model, a south-oriented office cell (width: 4.5m / depth: 6m / height: 3m) is investigated, consisting of three independent facade areas of 1m height each, including an opaque parapet (FA1) and two transparent facades areas (FA2/3). Both are equipped either with a movable shading- or a daylight redirecting system. The control of the façade system includes both: (1) a solar control to avoid overheating during summer as well as a (2) glare-protection control based on a luminance threshold on the inner side of the facade. The artificial light control is investigated in three different modes: (1) either constantly on during occupancy, (2) in on-off strategy based on daylight availability, or (3) continuously dimmed depending on the available daylight to supply up to 500lx on the work plane. The different scenarios are combined within three cases, which are listed in **Table 7-2**. Each case represents a stepwise improvement and is compared against the reference, which represents a simple case using a conventional shading screen for blocking solar radiation and continuously on artificial lighting during occupancy.

Table 7-2: Investigated case studies.

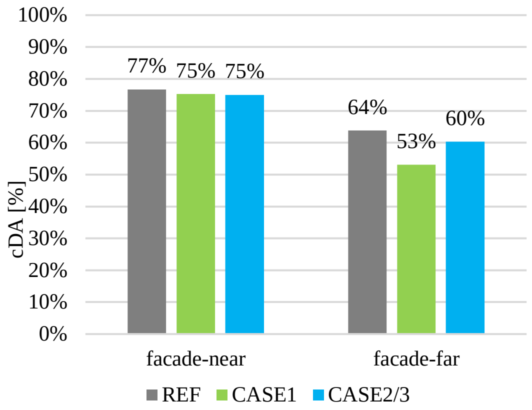
Investigated case	Façade and Artificial light settings
Reference case	Artificial light constantly on during occupancy Glazed façade + solar protection with exterior screen
Case 1 + daylight-depending lighting control	Light with on/off control based on daylight availability Glazed façade + solar protection with exterior screen
Case 2 + daylight redirection system	Light with on/off control based on daylight availability Glazed façade + shading Venetian blind (FB2) and specular Venetian blind (FB3)
Case 3 + lighting control & daylight redirection	Light with dimming control based on daylight Glazed façade + shading Venetian blind (FB2) and specular Venetian blind (FB3)

For the study evaluation, DALEC – “Day- and Artificial Light with Energy Calculation” is used. Intended as an early-stage design tool for lighting designers, architects, and building engineers, it enables an easy and fast evaluation of different façade solutions. Although easy to use, the software accounts for the complex thermal and lighting processes in buildings and allows a simple evaluation of heating, cooling, and electric lighting loads. Within IEA SHC Task 56, DALEC was validated and compared against several other dynamic simulation tools.

The investigated cases show a significant decrease in the artificial lighting energy demand by implementing a dimming control strategy while considering daylight availability. The visual comfort in terms of glare protection and sufficient daylight autonomy can be addressed properly through an enhanced control strategy of daylight redirecting blind systems. Daylight redirecting systems show benefits in all climates especially for daylighting in the façade-far area as well as for providing uniformity in the illuminance distribution. Nevertheless, it is always a balancing between solar entries (increasing cooling loads) and daylight availability (increased daylight autonomies). The results for continuous daylight autonomy in case 3 are equal to case 2, they only differ in artificial lighting due to enhanced dimming control.



(a)



(b)

Figure 7-1: Electric energy demand for heating, cooling, and lighting (a) and continuous daylight autonomy (b) for Stockholm.

7.3 Part B: Residential Building

7.3.1 Renovation case study of a multi-family house (project SaLüH!)

A multi-family-house (MFH) with decentral system for heating and domestic hot water (DHW) preparation and a photovoltaic (PV) field was performed in the CARNOT/Simulink simulation environment in order to evaluate the potential to reduce the purchased grid electricity. PV electricity is self-consumed covering electric power requests for heating, DHW preparation, ventilation, and appliances. Several technologies are considered in order to investigate different concepts. Electric system, heat pumps (HP), and a combination of those are considered for the space heating and DHW system. Moreover, four PV installation (no PV, roof, façade, or roof+façade) are studied. In order to investigate the results, monthly and annual primary energy (PE) factors (fPE) are considered. Finally, a cost analysis is carried out to evaluate the economic convenience of the presented cases.

The results of the simulations show that just a small percentage (below 26%) of electricity demand can be covered from PV field energy. PV installation on the roof and PV installation on the façade leads to the same energy production if the PV area on the façade is 41% more than the roof only. The installation of a PV field also on the façade (in addition to the roof) of the flat does not reduce significantly the purchased electricity (-11% in best of cases), due to the low self-consumption. The use of daily electric storage could be evaluated to increase the self-consumed electricity (a maximum of 95% in the case of PV roof + façade).

The use of annual primary energy factors instead of monthly values overestimates the reduction of primary energy demand in all cases compared to the case without the photovoltaic system. A maximum reduction of PE demand of 24% (compared to the case without PV system) can be obtained in case PV is installed on the roof and façade and a monthly primary energy conversion factor with an annual average value of 1.64 is assumed. PE demand can be significantly reduced (-46% in case of HP for both space heating and DHW, the hourly profile of DHW, and PV on the roof and the façade) compared to the case without PV in case daily electric storage is considered. The saving of PE demand is slightly overestimated (between 1% and 6% depending on the case) in case of annual fPE compared to the case in which monthly fPE values are considered.

All the cases lead to primary energy savings compared to the reference case (electric system without PV). Concepts with PV on roof+façade are the only ones leading to a cost increase. PV on the roof shows to reach higher economic savings compared to the PV on the façade. The optimum case for PE and costs is the one with HP for both heating and DHW and PV installation on the roof.

7.3.2 HVACviaFacade

Based on the HVACviaFACADE research project solutions for a renovated multi-storey residential building with 12 flats were investigated and evaluated by comparing building and system simulation results against a reference HVAC technology for the same building.

For the simulation, the approach of a virtual average flat was chosen, which means that the heating demand of the flat is 1/12 of the entire building. The simulations were performed for the climate of Graz, Austria using the simulation software TRNSYS.

The investigated decentralized façade integrated solar technologies consist of a reference system and five alternative solutions. The reference system is a direct electric heating system for space heating and domestic hot water preparation. No PV system is included in this reference system. The five alternative solutions are:

- Reference system + 14.6 m² PV per flat on the façade
- Reference system + 34.9 m² PV per flat on the façade and the roof
- Air source heat pump using ambient air for heating and domestic hot water preparation, no PV
- Air source heat pump + 5.6 m² PV per flat on the façade
- Air source heat pump +14.6 m² PV per flat on the façade

The key performance indicators used for the evaluation of the concepts are the primary energy demand, using different primary energy conversion factors (monthly and annual factors), and the Life Cycle Costs over 20 years.

The analysis of the simulation results shows that, compared to the reference system, the primary energy reduction potential ranges between 20 and 110 kWh/m²a. The additional life cycle costs of the alternative solutions range between 1 and 8.5 EUR/m²a. The highest primary energy reductions, but also the highest costs, are achieved by those systems including a large PV system.

7.3.3 Variation of the Envelope and HVAC Quality and Cost-optimality for a SFH

A typical detached single-family house (SFH) is used as a case study to investigate the cost-optimal configuration of the envelope, HVAC technology, and integration of renewables (PV) for different European climates. The SFH with 2 stories and 140 m² of the treated area is described in detail in IEA HPT Annex 49. The following variants of the system are considered in the study:

- With and without mechanical ventilation with heat recovery (MVHR)
- Heating and DHW preparation: Direct electric, A/W Heat Pump (A-HP), ground sourced heat pump (GW-HP)
- With or without shower drain water recovery (SDWR)
- With or without PV: 5 kWp (30 4m² on the roof with 32.5 m²) + optionally 1 or 5 kWp on south façade (with 51.7 m² total opaque area with constant efficiency of 12.5 %)

The analysis is done in 2 steps:

1) Simple building, annual balance (PHPP), “EU reference” climate (Strasbourg STR) with 3 Building Envelope qualities: Passive House (PH), Low Energy House (LEH), Reference (Ref);
2) Simple building, dynamic simulation, monthly balance with different envelope qualities and in different climates.

For each climate 576 dynamic building and HVAC simulations were performed and analysed.

The cost-optimal combination of the envelope (wall, window), HVAC (MVHR, heat pump), and renewables (PV) depends on the climate. In all cases, the minimum of annual capitalized cost (investment, maintenance, and operation) vs. PE (or cost difference vs. primary energy savings) is relatively flat and a range of combinations delivers similar results. With the aim to compare for a set of given boundary conditions the influence of the climate on the cost-optimal solution, it can be clearly shown that there is a mathematical minimum at a PE of 90 kWh/(m² a) for cold climates and around 60 kWh/(m² a) for more moderate climates. Moreover, additional PE savings of about 50 kWh/(m² a) could be achieved with little extra costs. The integration of RE (here PV) in the building roof is required in order to obtain high primary energy savings. However, under the current boundary conditions, in particular, façade integrated PV in residential buildings seems not to be economically feasible.

Heat recovery can also significantly reduce primary energy demand. Yet, MVHR is not economic under the given boundary conditions but is recommended anyway because of comfort and air quality constraints. Shower drain water recovery is economic for some of the investigated cases, however, the potential savings are relatively low when combined with a heat pump (water heater). Only with direct electric water heating, it delivers significant primary energy savings but then on a relatively high level of PE.

If only the investment costs are considered, (which is in many cases the relevant criterion for a decision), the solutions with high PE savings clearly require also a higher investment, which an investor would try to avoid. Incentives are required to foster the implementation of low LCC solutions.

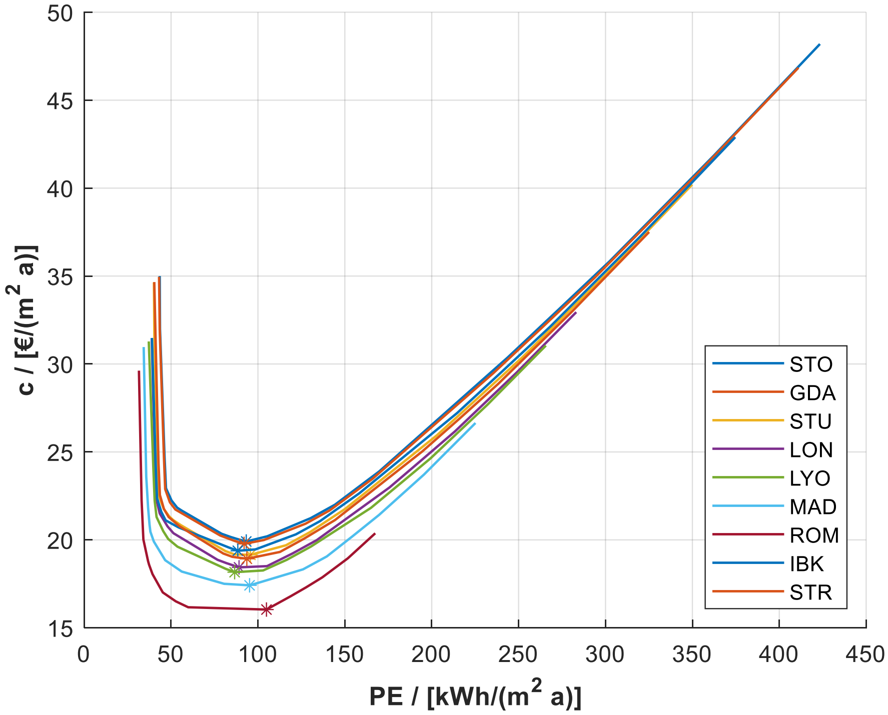


Figure 7-2: Curve with the lowest cost per PE for 9 different European climates

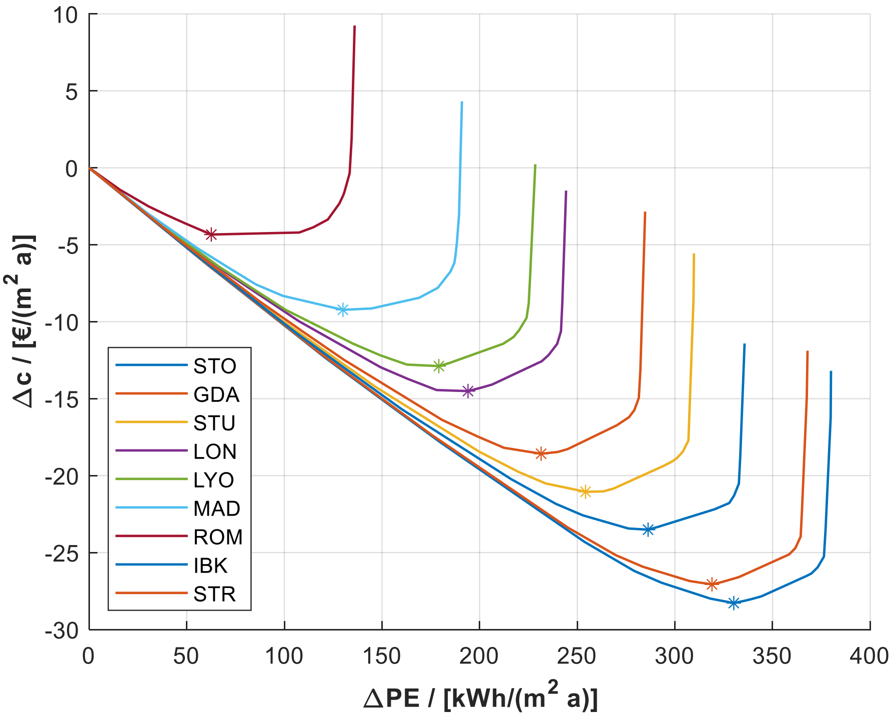


Figure 7-3: Curve with lowest cost difference per saved PE for 9 different European climates

8 Electricity Mix – Monthly PE conversion factors

Using a SFH in the climate of Stuttgart as an example cost-optimal solutions are determined with different primary energy conversion factors. Altogether 576 different combinations of envelope, heating system, MVHR, SDWR and PV are simulated and evaluated with respect to economic performance. Based on the simplified scenarios for the (future) composition of the electricity mix (see section 3.5), the different primary energy conversion factors represent different scenarios for the electricity mix and these are:

- constant acc. to EU (i.e. $f_{PEnon\text{-}RE}$ = 2.3) (see Figure 8-1)
- monthly scenario “10-10-10” for 10 % hydro, 10 % PV and 10 % Wind (see Figure 8-2)
- monthly scenario “10-30-30” for 10 % hydro, 30 % PV and 30 % Wind (see Figure 8-3)

Exemplarily cases with a heating demand of 15 kWh/(m² a) and MVHR and cases with 25 kWh/(m² a) without MVHR are highlighted (black dashed lines). The markers represent from high to low PE demands:

- Electric heating and DHW
- Electric heating and air source heat pump for DHW
- Electric DHW preparation and air source heat pump for heating
- Air source heat pump for heating and DHW
- Ground source heat pump for heating and DHW

In case of DE heating and DHW preparation, the PH (15 kWh/(m² a) with MVHR) outperforms the 25 kWh/(m² a) house. When DHW is done by a air-source HP still the PH has a lower PE consumption than the 25 kWh/(m2 a) house. Contrariwise, if DHW is done by direct electric heating and a heat pump is used for heating, the performance is similar and auxiliary energies gain importance. With an air source HP for DHW preparation and heating, both buildings perform comparably. However, with a ground source HP, the overall consumption is even lower in case of the 25 kWh/(m² a) house, because of the rel. high auxiliary energy of the MVHR. Remark: It has to be highlighted that in heating dominated climates such as in Stuttgart, solutions without MVHR are not recommended because of IAQ and comfort constraints.

With future increasing share of RE in the electricity mix, on-site RE will lead to lower overall absolute PE savings. Furthermore, solutions such as the ground source heat pump that reduce the winter demand more than an air source heat pump show better performance. Also integration of (on site) PV into the HVAC system becomes less economic when a future energy mix with a high share of PV is considered.

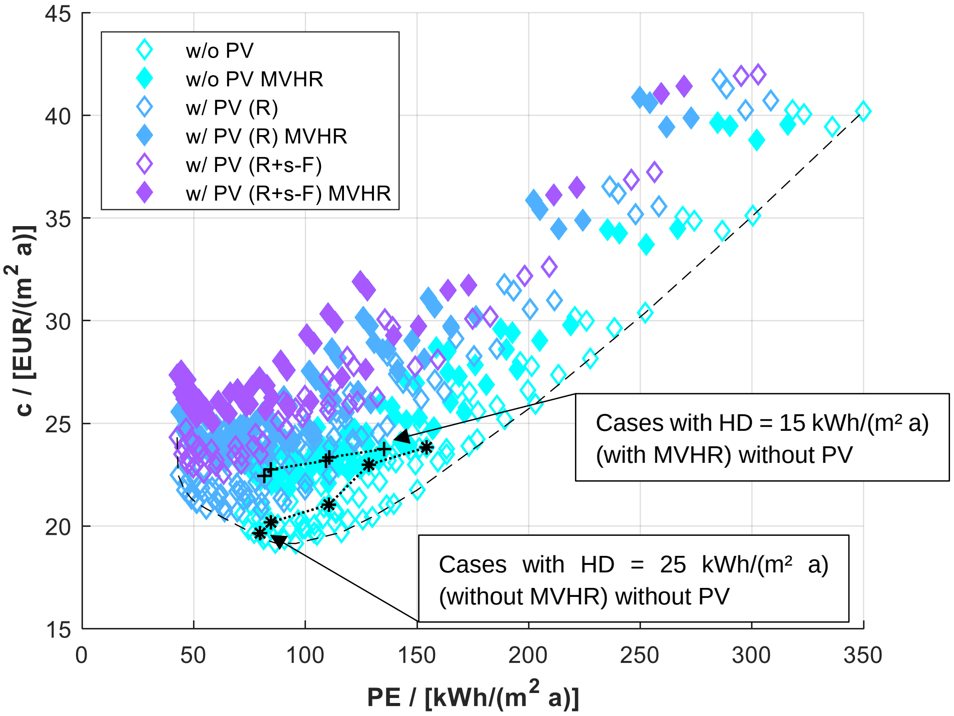


Figure 8-1: non-RE vs. specific capitalized costs with constant PE conversion factor (SFH, Stuttgart)

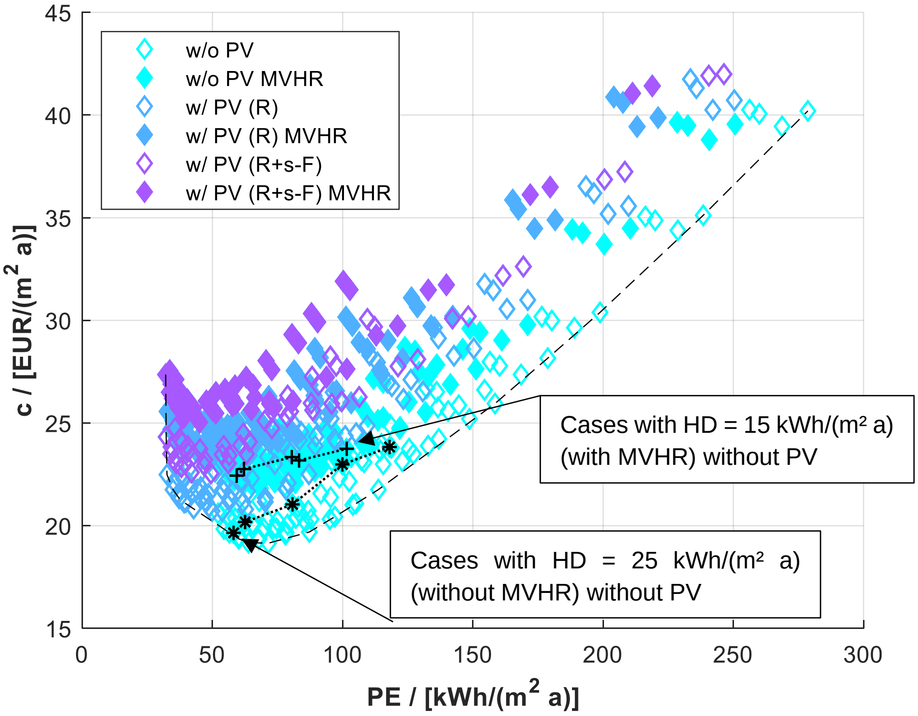


Figure 8-2: non-RE vs. specific capitalized costs with monthly PE conversion factor, scenario "10-10-10" factor (SFH, Stuttgart)

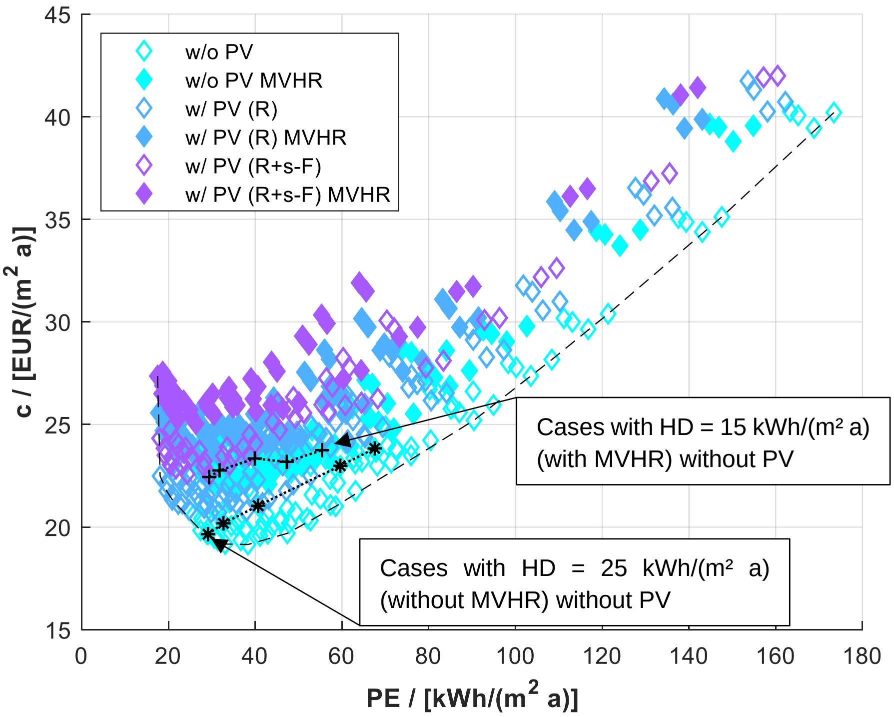


Figure 8-3: non-RE vs. specific capitalized costs with monthly PE conversion factor, scenario "10-30-30" factor (SFH, Stuttgart)

On a net balance basis, significant seasonal aspects are disregarded. This is - in particular in heating dominated climates - the mismatch between solar availability and energy demand (for heating, DHW, aux. and appliances). On a net balance basis, electricity produced in summer and injected to the grid would have the same value as electricity purchased from the grid in winter for heating, etc.. However, this assumption does not hold now and will be even more critical in future with higher shares of PV in the electricity mix. This seasonal mismatch or also called “winter gap” would still be existent even if seasonal storage will be available in the future as it will be associated with storage and conversion losses. Furthermore, at net balance disregards the aspect that the performance of air source heat pumps is strongly affected by the seasonal variation of the ambient temperature. The suggested simplified scenarios for the electricity mix and the consideration of its influence on the overall building performance by means of monthly primary energy factors allows to evaluate the performance considering these seasonal effects and enables an optimization including the effect of the composition of the (future) electricity system. System solutions, which contribute to electricity savings in winter will outperform solutions that mainly contribute to electricity production in summer.

9 Summary and Conclusions

In this report (DC.3 of IEA SHC Task 56) guidelines for the integration and evaluation of building-integrated solar envelope systems (BISES) were suggested based on simulation and monitoring results elaborated within IEA SHC Task 56. BISES includes several active components such as photovoltaic (PV), solar thermal (ST) and photovoltaic-thermal (PVT), and also daylighting components, integrated into the HVAC system of a building. The HVAC system includes heating, cooling (dehumidification) and DHW preparation. Both passive technologies such as mechanical ventilation with heat recovery (MVHR) and shower drain water recovery (SDWR) and active technologies such as direct electric (DE) heating, air heat pumps (A-HP) and ground water heat pumps (GWHP) are considered.

Within the IEA SHC Task 56, a methodology for the evaluation of BISES on building level was suggested and case studies were investigated accordingly. Simulation results of different case studies are presented in detail in the report DC.2 and results of monitoring projects can be found in the report D.C4. The design guidelines are based on the experience and contributions of the IEA SHC Task 56 and aim to support designers and planers of energy efficient buildings to evaluate and optimize integration of BISES. Virtual case studies were examined by means of numerical simulation. The first step was a comparison and parameterization of an office cell in several calculation and simulation platforms such as:

- Energy+
- TRNSYS
- IDA ICE
- Modelica
- Matlab/Simulink (CarnotUIBK)
- Matlab/Simulink (AlmaBuild)
- DALEC
- PHPP

Simulations were performed with three European climates (cold: Stockholm, moderate: Stuttgart, warm: Rome), which represent heating and cooling dominated climates as well as different solar potential. Furthermore, in some specific case studies other European and non-European local climates were considered, e.g. Graz (AUT), Innsbruck (AUT), Stuttgart (GER), Strasbourg (FRA), Eindhoven (NEL), Montreal (CAN). In addition to the virtual case studies, some demo cases were analyzed. Theses case studies for residential and non-residential buildings are summarized in the following table:

Table 1: Overview of Case Studies with Solar Façades, residential (SFH, MFH) and non-residential (office) buildings

Non-Residential
1 Envelope, MVHR, HP, PV var. climates (office cell)
2 Lighting, HP, PV, Battery (office cell)
3 Shading / daylighting control (office cell)
4 Advanced daylighting (office cell)
5 Solar Thermal Façade (office building)
6 PVT for air pre-heating (office cell)
7 Varennes Library, Canada (PVT, DEMO)
8 Copenhagen Int. School, DK (BIPV, DEMO)

Residential
1 SFH – Envelope, MVHR, HP, PV, SDWR
2 MFH (MVHR, HP, PV)
3 MFH (MVHR-HP, PV)
4 MFH An-der-Lan (At) – PV Façade (IBK, DEMO)
5 Solar Decathlon (Concordia, DEMO)

For all virtual case studies, primary energy savings and the capitalized total annual costs were evaluated. A techno-economic analysis of different technologies including passive components (envelope, mechanical ventilation with heat recovery (MHVR), shower drain water recovery (SDWR)), active components (heat pump) and renewables (ST, PV, PVT) was performed. Cost-optimal solutions based on suitable combinations of passive and active technologies can be identified depending on the climate and type of building i.e. residential buildings and non-residential buildings as well as application (heating, cooling, DHW, lighting, appliances). The cost efficiency of different technologies was evaluated vs. their primary energy savings. Table 3 gives an overview about the key performance indicators that were used to evaluate and compare different solar façade systems.

Table 3: Key Performance Indicators (KPI)

KPI	Description
TC	Thermal Comfort: Operative temperature ϑop / [°C], relative humidity rH / [%]
IAQ	Indoor Air Quality: CO_2 / [ppm], relative humidity rH / [%]
VC	Visual Comfort: glare protection (cd/m2, DGP)
DP	Daylight Provision: daylight autonomy (DA, cDA, sDA)
FE	Final Energy (delivered energy) / [kWh/(m2 a)]
LCF, SCF	Load Cover Factor, Supply Cover Factor
SF	Solar Fraction
PE	Primary Energy PE / [$kWh_{PE}/(m^2$ a)]: monthly PE conversion factors
TAC	Total annual cost / [€]: Capitalized investment costs, operation and maintenance
CI	Cost intensity CI = ΔTAC/ΔPE / [€/$kWh_{PE,saved}$]

Some general conclusions can be drawn based on a techno-economic analysis, but it is noteworthy that specific recommendations might depend on the type and characteristics of the building, the climatic zone, the aim of use, the local boundary conditions, and last but not least personal interests. The guidelines given in this report are based on a life cycle cost (LCC) analysis, following for the most part the recommendation of the EU for nearly zero energy buildings (nZEB) within the energy performance for buildings directive (EPBD). Reality is, however, that decisions are still frequently based on the minimization of investment costs.

In order to obtain high primary energy (PE) savings at a cost-optimal level, the first step should always be reducing the energy demand by means of passive and active measures, and then integrating renewable energy (RE) into the building and the HVAC system. Low energy demands also lead to lower loads, which allow downsizing of the system and reducing HVAC and RE investment costs. In order to be able to calculate possible savings that can be obtained by integrating RE, the energy demand has to be predicted correctly, at least on a monthly basis. A correct prediction is also the basis for appropriate system sizing. Both under-sizing and over-sizing must be avoided in order to prevent discomfort (under-heating, over-heating), suboptimal performance, shorter service life of equipment (on/off cycling), and higher investment costs. Building and HVAC simulations can support both optimal system design and accurate prediction of possible savings and the associated life cycle costs. Furthermore, sufficient indoor air quality, as well as thermal and visual comfort can be proven for each solution.

The energy request in office buildings is mainly due to lighting and other electric plug loads. Daylighting can have a significant contribution to improve the overall building performance and the use of LED instead of fluorescent light is highly recommended. The available surface for RE is generally relatively low compared to the treated area. Furthermore, in most climates, particularly in buildings with good envelope quality, cooling is more dominating than heating. Therefore, a significant self-consumption of the electricity from RE is usually possible. The contemporaneity of energy production and consumption (presence of persons and appliances during the day) contributes to high levels of self-consumption. Different results for cost-optimal solutions are obtained when heating or cooling dominated climates are compared. Overall, BISES in combination with an improved envelope can lead to a significant reduction of imported (grid) electricity. The implementation of heat pumps appears to be beneficial but under the current boundary conditions, BISES requires subsidies in order to be competitive. In particular the use of batteries to increase self-consumption is not economically feasible. Moreover, daylight analyses were carried out showing possible solutions to reduce energy use and improve visual comfort at the same time. The implementation of a dimming control strategy allows significantly decreasing the artificial lighting energy demand. The balance between passive solar yields (with increasing cooling loads) and daylight availability (increased daylight autonomies) is case sensitive and has always to be considered.

In the residential sector, the appliances have a significant contribution to the total energy demand and should not be disregarded. In moderate and cold climates, the main energy request is due to space heating and domestic hot water (DHW) preparation. The better the building envelope, the more relevant the DHW demand is. Cooling can have a significant contribution in warm climates, but cooling (if kept in acceptable limits by means of passive measures) is less critical as loads occur mainly during daytime and in summer when solar energy is available. High-performing residential buildings still have a considerable high demand because of DHW preparation, auxiliary energies, and appliances, which can at least partly be covered by RE. In the case of single family house (SFH), there is usually a quite large available area for RE, therefore a net-zero energy balance is possible. However, dynamic simulations show that the self-consumption is relatively small with load cover factor (LCF) only in the range between 15 % and 40 % for moderate and up to 50 % for warm climates with a supply cover factor (SCF) of up to 50 % for smaller PV systems and only 25 % for larger systems. Instead, for multi family houses (MFH), a high variability has to be considered due to possible size, shape, and number of stories. Usually, the available roof area is small in relation to the treated area and exploiting the façade in addition to the roof is more relevant. In the residential sector, MVHR turned out to be not economic but is anyway recommended in order to maintain the same level of indoor air quality with extract air ventilation avoiding discomfort situations (cold air). Application of shower waste water recovery (SDWR) is economic in some cases, but it does only contribute significantly to PE savings in case of direct-electric (DE) DHW preparation, which should be avoided. In the case of air-HP and particularly in the case of ground water heat pump (GW-HP) there is only a relatively small benefit. The application of photovoltaic PV allows reducing the PE to zero in many cases. The cost-optimum curve is relatively flat, and several combinations lead to similar annual capitalized cost and PE savings. The climate influences the cost-optimal combination of envelope, HVAC, and renewables. It is noteworthy that the assumption of the cost parameters (such as electricity prices, price development and local variation of equipment and installation costs) and the user behaviour are important factors and can significantly affect the results. In the European context, the use of BISES resulted in low levels of PE in moderate to warm climates. However, reducing PE is cost-effective in cold climates, unless very high PE savings should be achieved.

The potential PE savings of BISES on building level were analysed for different scenarios of the (future) energy mix composition by applying monthly primary energy factors. It could be observed that the electricity mix influences the composition of the optimal solution and the ranking of different technologies. With (future) higher shares of renewables in the electricity mix, on-site RE becomes less beneficial, instead technologies that reduce the energy demand in winter, such as passive solutions, heat recovery, or heat pumps, would outperform BISES.

If only the investment costs are considered, (which is still in many cases the relevant decision criterion), the solutions with high PE savings clearly require also higher investments. Hence, incentives are required to foster the implementation of cost-optimal high PE saving solutions.

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11 Appendix

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