Optimization of Helsingborg's concert hall with regards to nZEB balancing.

Marie Chevalerias[1] marie.chevalerias.022@student.lu.se,
Amanda O'Donnell[1] amanda.odonnell.769@student.lu.se,
Magda Stefanowicz[1] magdalena.stefanowicz.276@student.lu.se
[1]Division of Energy and Building Design and Division of Building Service, Faculty of Engineering, Lund University, Sweden

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SUMMARY
Helsingborg's concert house is a landmark of modernistic architecture in Sweden, designed by renowned architect Sven Markelius and constructed in 1932. This paper exposes the building's current energy balance and evaluates possible energy reduction solutions and potential to maximize on-site solar production in order to approach an annual net-zero energy building balance. Results show a potential to decrease the energy demand of the building by 71% and provide 91% coverage of annual electrical demand with solar technology. All measures are assessed with reverential regard to the building's prominent national and cultural heritage value. Profitability and economic discrepancies for all measures are continuously assessed.

INTRODUCTION
The concert house can, apart from facilitate musical performances, host smaller conferences, private rehearsal rooms and office spaces for employees of the facility. The building has a relatively compact shape and a favorably low window to wall ratio of 8%. The load bearing structure is of brick and concrete with few insulating measures applied to the original design.
Helsingborg has a humid, continental climate with few daylight hours in winter (6h53 min) and substantially more daylight in summer (17h43min). Similarly, the median cloud coverage from October to April is high. (Cedar Lake Ventures, Inc., 2012) (see Appendix)
The annual heating demand is significant, with notable variations subject to seasonal extremities and activity profiles within the building. The electricity demand is seemingly constant throughout the year, except during summer when the spaces are more or less unoccupied. Moreover, there is a large and unobstructed flat roof area on which solar potential is favorable and will be evaluated in order to approach net-zero energy balance.
The project aims to reduce the building's energy demand and maximize production over the year, widening the time at which the building could be self-providing at a reasonable life cycle cost (LCC).

METHODOLOGY
Pre-study
A pre-study containing a local climate analysis, an urban analysis, a simplified profitability analysis of solar energy performance at varying irradiation levels, as well as an evaluation of the effect of tilt and orientation on the productivity of a photovoltaic (PV) system was made.
The pre-study served as an initial indication of the potential of the building with regards to energy optimization and economic viability of solar energy.
The local climate analysis focused on solar irradiation and shading of the building and was made with DIVA4RHINO in Grasshopper and Ecotect from Autodesk respectively. The effects of these parameters on PV and solar thermal (ST) productivity were considered with shading masks in System Advisory Modelling Tool (SAM).
The urban analysis served to evaluate the public visibility of the building as shown in Figure 11.

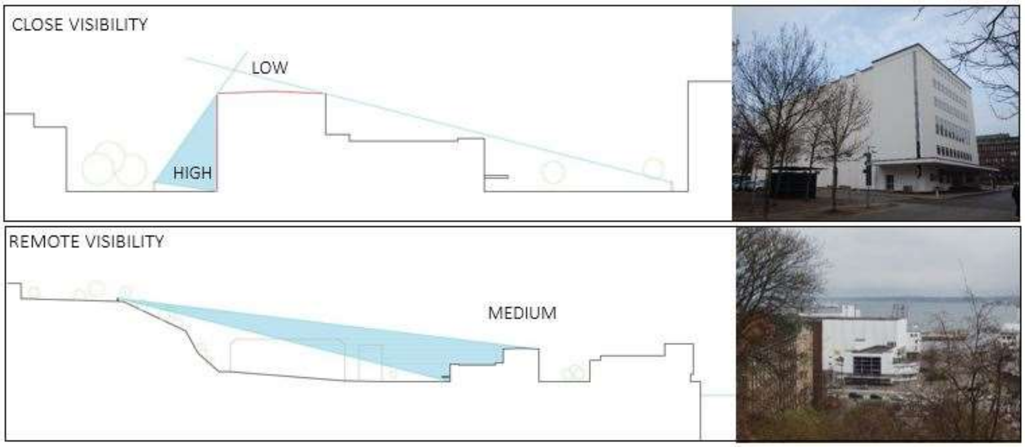

Figure 1, Schematic drawing of the visibility of different parts of the building with the corresponding photograph of the view.

According to the perceived visibility and sensitivity of the building, an acceptability grid was completed according to the LESO-QV method to define the required quality of integration of solar systems on different surfaces.

The irradiation levels at which $1m^2$ of PV and ST are profitable were analyzed with simplified economic input data, shown in Table 1, to steer the placement of the technologies. The investment cost is limited to the module itself. The PV was later calculated with 20000 SEK per kWp for the whole grid connected system. The nominal interest rate, nominal price change and inflation were used according to Table 1 throughout the project.

Table 1, economic data for the profitable irradiation study

	1 PV panel	1 ST collector
Investment cost/(SEK/m²)	4300	3500
Life time of the system/years	25	15
Nom. price chage rate, kp/%	(Electricity) 5.2	(Heating) 3.2
Nom. interest rate, i/%	3	
Inflation/%	1.2	

The output of a typical solar thermal collector in Sweden was determined with Björn Karlsson's formula: $$Q = \eta 0 \cdot Gyear - F'UL \cdot (Tm - Ta) \cdot t$$

Assuming:

Gyear = 800 kWh/m²year (sum of useful irradiation in a year)

t = 1270 h/year (operating time in a year)

Ta = 13°C (average ambient temperature)

Tm = solar collector temperature (mean value of heat carrier fluid) (°C)

UL = heat loss coefficient (W/m2K)

η0 = F´·(τ·α)

F´ = collector efficiency factor

τ = transmittance of glazing

α = absorptance of absorber

(τα) = effective transmittance-absorptance product

The output in kWh of a PV was calculated with a simplified formula (Bernardo, 2014)

$$E = \phi \cdot Ppeak \cdot H$$

Where:

Φ = correction factor of 0.85

Ppeak = 0.215 kW

H= the irradiation in kWh/m² at 25°C and normal incidence, assumed to be 1200 kWh/m²,year in south of Sweden.

Throughout the project work, the NPV was determined with the gradient formula:

$$NPV = \left[A_1 \frac{(1-(1+g)^n.(1+i)^{-n}}{i-g}\right] - A_0$$

Where:
$A_{0,1}$ = Cost at year 0,1
n= the year for which the NPV is calculated
g= Nominal price chage rate, kp
i= Nominal interest rate, i

Further, the effect of tilt and orientation on the productivity of a PV system of 10 m² was made with SAM. The weather file used for the analyses was for Copenhagen.

Energy balancing

Initially, the current annual energy demand data (provided on an hourly basis) was inserted and evaluated in the dynamic energy simulation software, DesignBuilder. (See settings in Appendix)
The energy balance of the building was separated into a heating and electricity balance, for which energy saving and production potentials were analyzed separately. The balancing process was based both on achieving the nZEB concept of producing as much energy on site as the building uses on annual basis, as well as on minimizing the costs.

Heating Balance

The potential to compensate the heating demand with heat production from ST was evaluated with a building applied solar thermal system (BAST), modelled in SAM. The economic viability of the solution was addressed with a sensitivity analysis, comparing payback times for varying magnitudes of energy prices, nominal interest rates and nominal price change rates.
The price of the complete system was estimated by adding 40 000 Swedish Kroners (SEK) to the price of module per m².
The potential to reduce the building's heating demand was assessed with a parametric study in DesignBuilder.
Additional analysis of the thermal situation was made with, firstly, a life cycle assessment (LCA) of adding internal insulation to the building for a 50 year period. The LCA was made with Gabi 6 software. Secondly, a moisture risks assessment associated with adding internal insulation was conducted according to the ByggaF procedure. Thirdly, the thermal comfort as a result of suggested energy saving measures was analyzed.

Electricity balance

The building's annual energy demand was calculated by weighting and accumulating use patterns of 365 days in 2013. The varying use patterns of the building were chosen to be represented by three design day scenarios; a concert day, a rehearsal day and an office day (see Appendix). Overproduction calculations were based on the weighted design day energy usage, however difference between monthly, daily, weighted design day and three days scenarios was also studied (see Appendix).
Initially, no electricity saving measures were applied to the analysis due to lack of information in this regard. Hereby, focus was kept to the electricity production potential of installed PV. For electricity production, four cases were identified and evaluated. The first, building applied photovoltaics (BAPV), the second - an external structure to maximize the PV area and reduce the interference in the existing building, the third – the external structure redesigned in accordance to SAM PV production study and finally, the fourth – the external structure redesigned in accordance to irradiation study conducted in Grasshopper. Next, these four cases were compared in terms on annual production, total kWp and initial cost. As a results, two suggestions were chosen for further studies. As a last step in electricity balancing, the assumption of 25% savings of electricity use for lighting was made based on a lecture *on Energy saving potential and strategies for reducing electric lighting* (Dubois, Lecture 2014), a lighting control system could be installed to control absence and thus reduce the lighting schedule.

The economic viability of these two suggestions was addressed with a sensitivity analysis, as explained for ST above. The investment cost for the PV system was estimated with a module price of 20 000 SEK/kWp and a cost for inversters of 10 000 SEK with a lifespan a 8 years.
The LCC of the PV systems also included the aspect of buying and selling on-site produced electricity, as shown in Figure 2, composition of bought electricity and on-site produced sold electricity.Figure 2, and how the profitability is affected by the electricity price plans, certificates, tax reductions and subsidiaries.

Figure 2, composition of bought electricity and on-site produced sold electricity.

RESULTS
Pre-study results
The acceptability grid places the building on a high level of requirement for the quality of the solar system integration since the building combine a highly sensitive zone with different level of visibility resulting in the bold characters in Table 2.

Table 2, acceptability grid

ACCEPTABILITY GRID		ZONE SENSITIVITY		
		LOW	MEDIUM	HIGH
FIELD VISIBILITY	LOW	0	1.5	**3.5**
	MEDIUM	1.5	3.5	**6**
	HIGH	3.5	6	**9**

Figure 3 presents a plan view of the building with the shadow range for the spring equinox. The only shadow on the biggest roof surface is created by the Air Handling Unit (AHU).

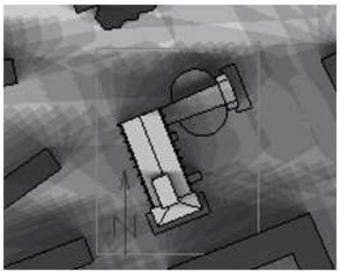
Figure 3, shadow range on spring equinox

Figure 4 presents the solar irradiations on the buildings in plan and elevation views with 4 levels scale. The roof and parts of the south façade have an irradiation level between 650 and 1100 kWh/m2.

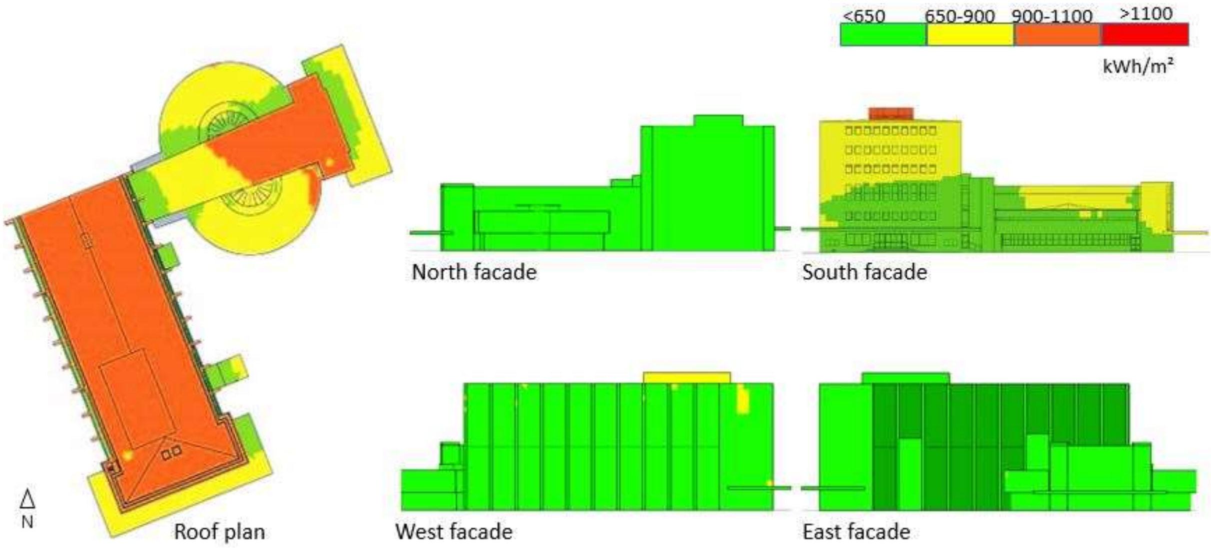

Figure 4, annual solar irradiation on the building

The profitability study presented in Figure 5 reveals that an annual irradiation of 700 kWh/m² seems sufficient to make a PV panel profitable whereas the ST collector requires 1100 kWh/m² to see its investment cost paid back before the end of its lifespan.

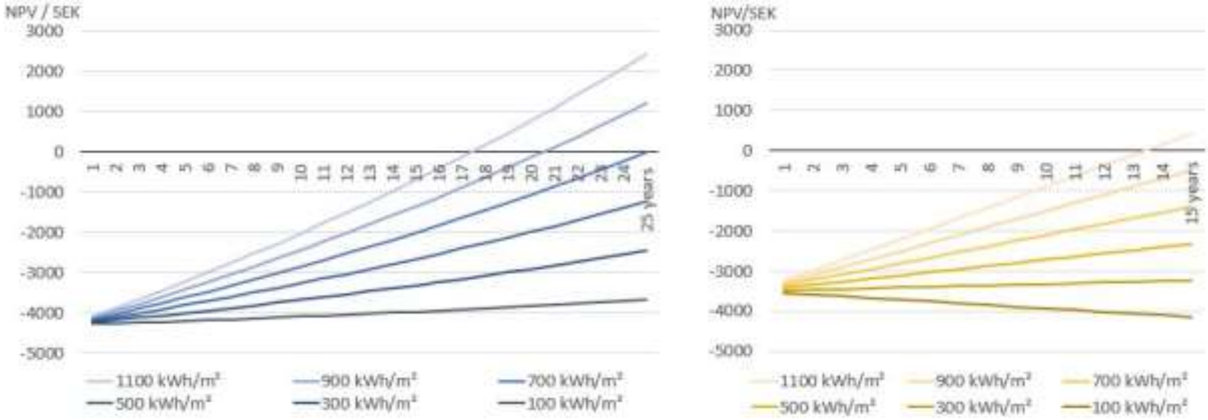

Figure 5, NPV of 1m² solar PV panel (left) and ST collector (right) over their respective lifespan with different solar irradiation

The effect of orientation and tilt on the performance of a 10 m² PV system for both solstices and the spring equinox is presented in Figure 6. For a PV array oriented at 158º azimuth, the optimum tilt is 20º in June, 50º in March and 70º in December.

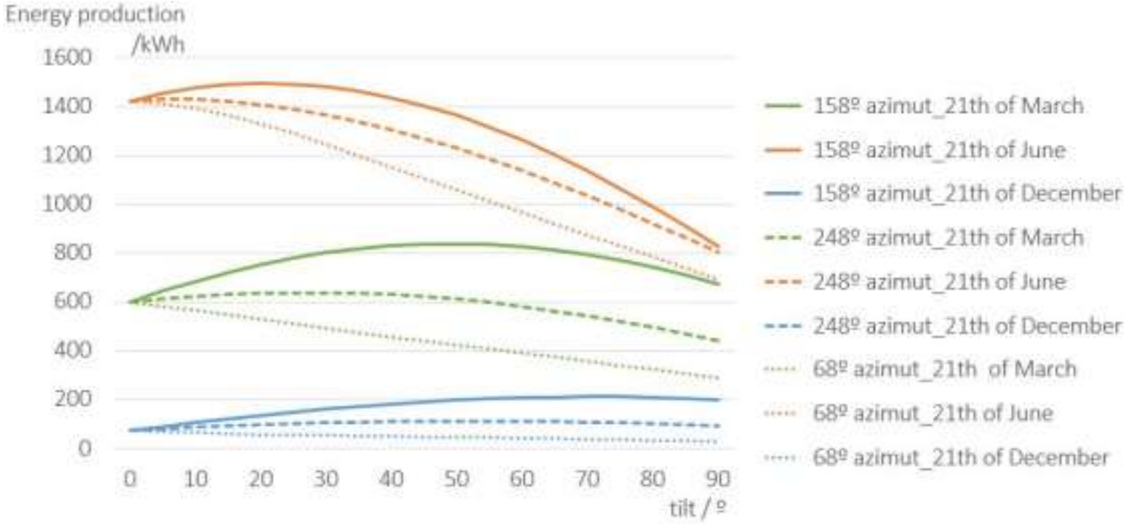

Figure 6, energy production of a 10 m2 PV system at different tilt, azimuth and season

Energy balancing

As can be seen in Table 3, the DesignBuilder model results in similar heating and electricity demand compared to the actual measurement of 2013.

Table 3, DesignBuilder model output compared to the measured energy demand of 2013

	Measured in 2013	DB model	% difference
Heating/ (kWh/m²)	79.10	78.09	1.3 %
Electricity/ (kWh/ m²)	36.73	36.33	1.1 %

Heating balance

As shown in Figure 7, the heat production by ST covers a very small part of the heating demand since the system is sized to avoid overproduction. In summer, the highest production point of the system meets the lowest heating demand of the year.

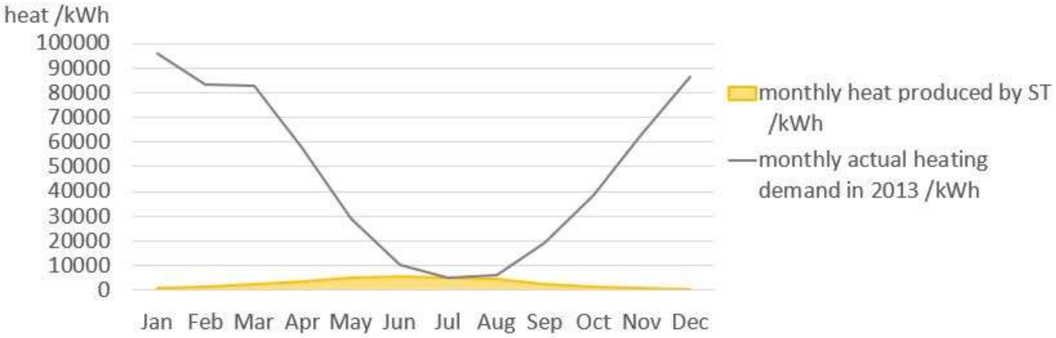

Figure 7, heating demand vs heat production by ST system

The system simulated in SAM to achieve this production corresponds to 56 flat plate collectors oriented at 158° azimuth with a 30° tilt.

The NPV calculation for this system, presented in Figure 8, shows that having a ST system starts to be more profitable than buying heat from the district heating after 12 years, however the investment cost is not paid back at the end of the collector's warranty. The sensitivity analysis on the right indicates for which combinations of nominal heating price change rate and nominal interest rate the system would get paid back before 15 years (above the grey line).

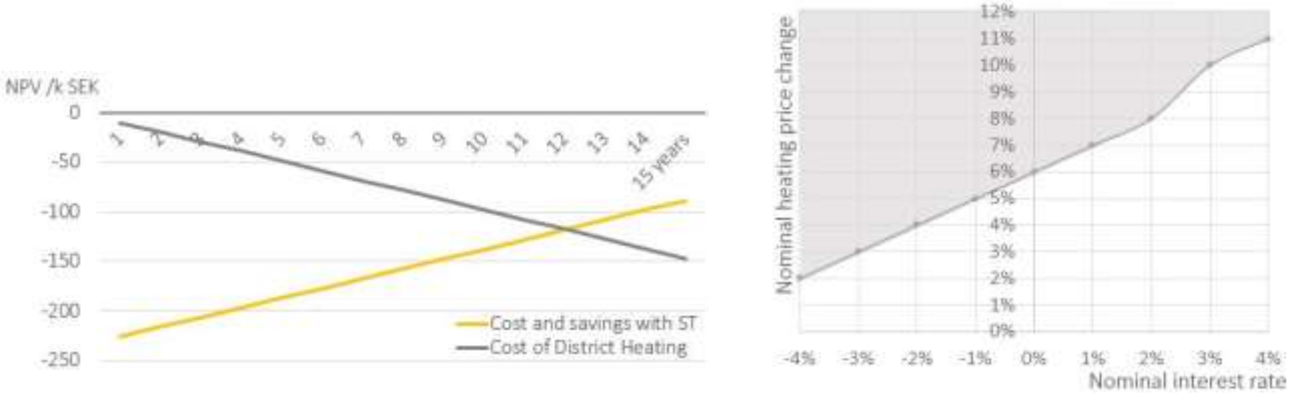

Figure 8, NPV for ST system (left) and sensitive analysis of beneficial interest rate for this system (right)

The parametric study in Figure 9 shows that increasing the efficiency of the heat recovery (HR) from 60 % to 85 % and insulating from inside the walls with 20 cm EPS are the most efficient measures to decrease the heating demand of the building. (For the description of the changed settings, see Appendix)

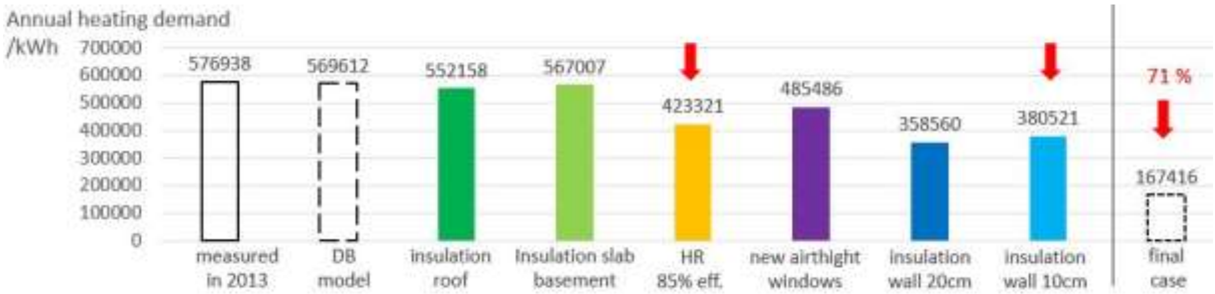

Figure 9, parametric study on passive measures to reduce the heating demand

However the LCC analysis of these measures, presented in Figure 10, suggests that an insulation thickness of 10 cm is sufficient in terms of financial savings. Since the payback time is 9 years instead of 15 for the double of thickness. Therefore, the final case combines a more efficient HR and 10 cm inside insulation of the envelope and results in a reduction of 71% in heating demand.

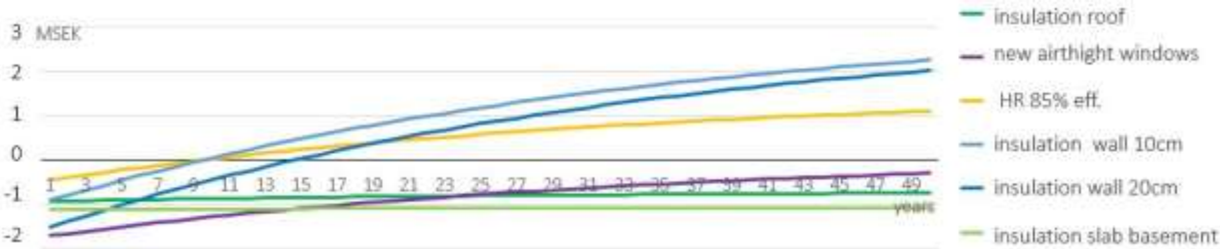

Figure 10, NPV over 50 years for each heating reduction measures.

Another advantage of choosing a smaller amount of insulation is to limit its environmental impact. Table 4 shows that reducing the heating consumption by applying insulation appears to be beneficial for the environment despite the production of material, except regarding the ozone layer depletion potential which increase significantly.

Table 4, relative difference of environmental impact in selected categories by applying insulation. LCA over 50 years

	% difference with insulation
Acidification Potential / [kg SO2-Equiv.]	-32%
Eutrophication Potential / [kg Phosphate-Equiv.]	-32%
Global Warming Potential / [kg CO2-Equiv.]	-33%
Ozone Layer Depletion Potential / [kg R11-Equiv.]	**+ 177%**
Photochem. Ozone Creation Potential / [kg Ethene-Equiv.]	-19%
Primary energy demand from ren. and non ren. resources / [MJ]	-32%
Total freshwater use / [kg]	-33%

However, applying insulation from the inside has been identify in the risk assessment below as a very high risk which probability of occurrence could be reduced by a well-designed air gap.

Table 5, moisture risk assessment for applying insulation on the inside of the wall

Factor	Description of risk	P	C	R	improvement	P	C	R
Moisture diffusion	Moisture damage in the interior insulating layer	3	3	9	Air gap allowing moisture to evacuate	2	3	6

Another consequence of applying insulation is the modification of the indoor thermal comfort with increase of the operative temperature.

Figure 11 shows that the circulation area benefits from the improvements by never being under 19ºC. On the other hand, the offices are getting too warm in summer with temperatures between 27 ºC and 28ºC which could be prevented by using shading devices.

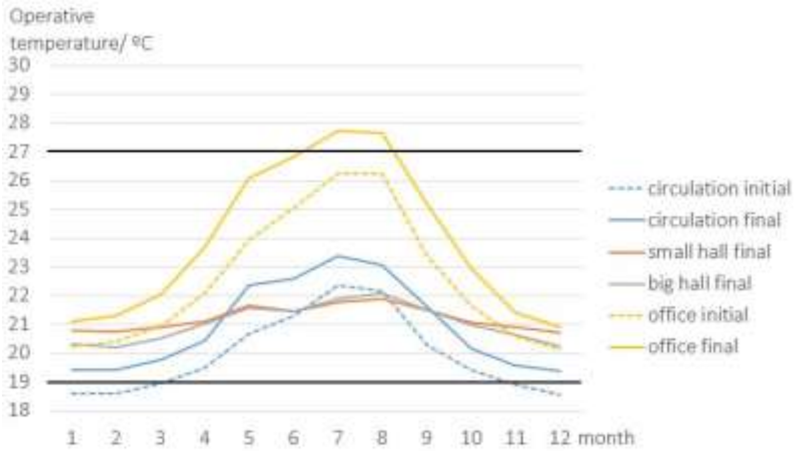

Figure 11, operative temperature over the year for the four occupied zones

Electricity balance

Four cases identified and evaluated in terms of electricity production are shown on Figure 12 and Figure 14.

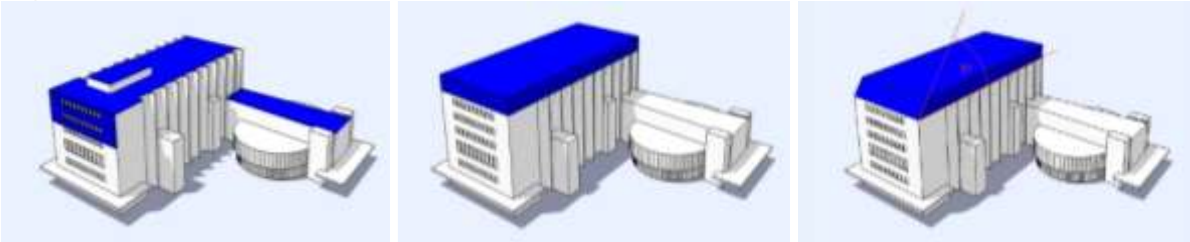

Figure 12, Three, of four, PV system designs: BAPV, OUR BOX and SAM BOX accordingly.

The irradiation study in Grasshopper shows that optimal tilt of the southern surface on the PV structure appears when the roof is fractured in 80% of its length, as shown on Figure 14. Electricity production for the analysed case expands more towards autumn, winter and spring while the annual production is still high

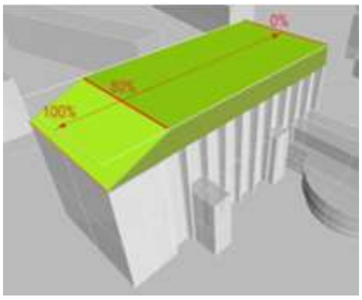

Figure 14, Fourth PV system design, DIVA BOX.

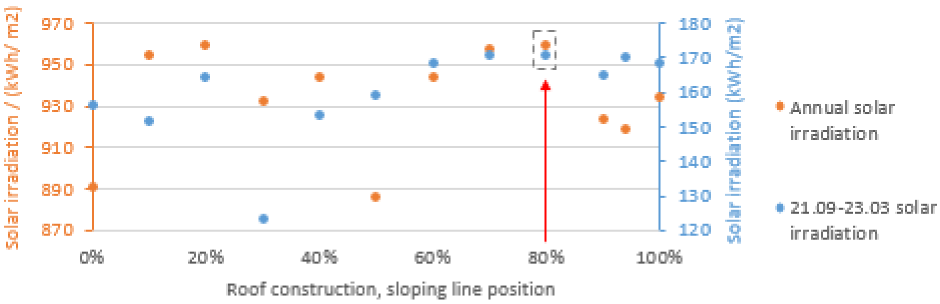

Figure 13, Annual and seasonal irradiation study results from Grasshopper

Annual electricity production, kWp and initial costs of the analysed systems show significant advantage of BAVP and DIVA BOX designs. Both cases have higher energy production per PV area, as a consequence they costs less per kWp of the systems.

Figure 15, Annual electricity production and PV systems cost of the four cases.

Further analysis of the two solutions, BAPV and DIVA BOX, show that the annual production profile of DIVA BOX is lower in summer and slightly higher in autumn, winter and spring (see Figure 16). However, when the production results are calculated in terms of economical savings due to overproduction price change during the year, the two design do not vary visibly, see Figure 17

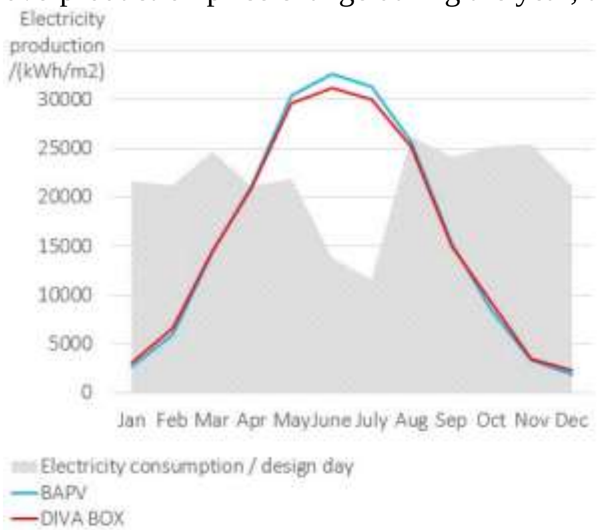

Figure 16, Annual electricity production vs. consumption

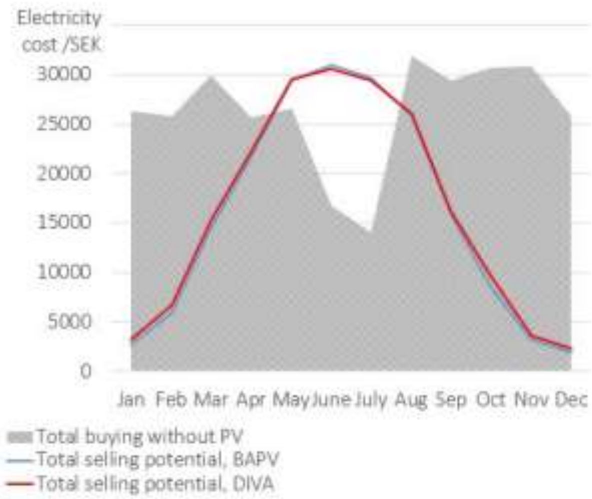

Figure 17, Annual electricity cost balance

Hourly electricity production profile in relation to the weighted design day, is shown in the appendix. LCC analysis of BAPV and DIVA BOX solutions show the importance of selling the electricity overproduction to the grid. As shown on Figure 18, the only way to pay back the initial costs of the BAPV PV within its guarantee time of 25years, is to sell the unused energy. The sensitivity analysis on the right indicates for which combinations of nominal electricity price change rate and nominal interest rate the system would get paid back before 25, 22, 20 and 15 years (above the lines).

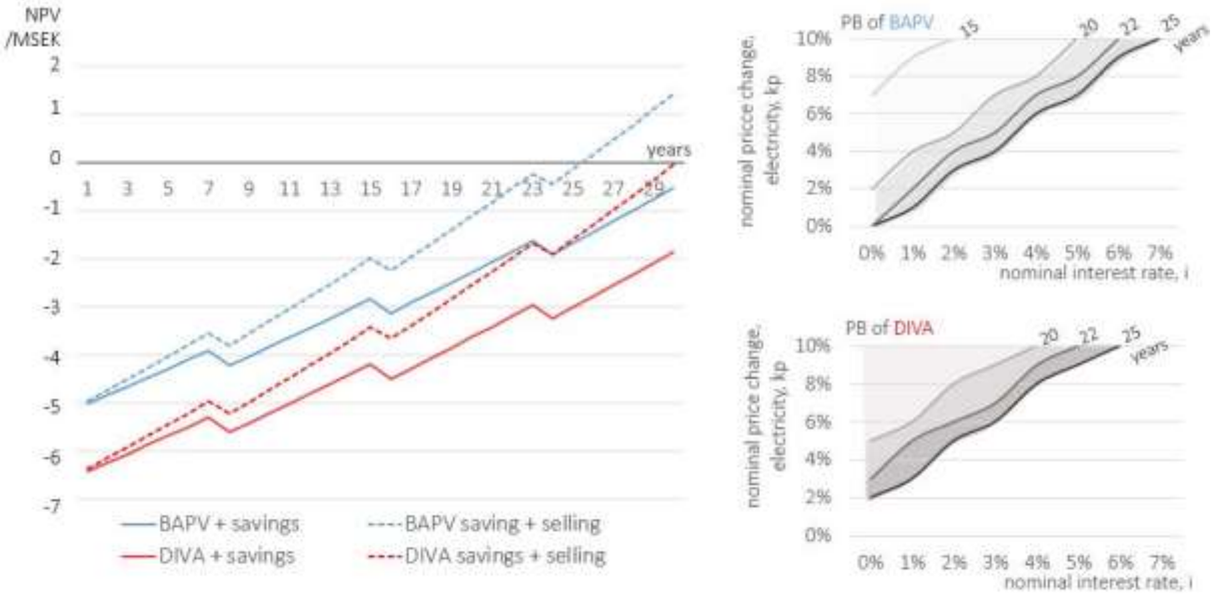

Figure 18, NPV for BAPV and DIVA BOX solution (left) with corresponding sensitivity analysis (right)

Lighting electricity use and its reduction potential results show high importance of this aspect. As shown in appendix, according to DB simulations, 71% of total electricity use is lighting. Thus when lighting electricity demand is reduced by 25%, as a consequence of introducing the control system, the total electricity demand value results in value of 196665 kWh/year.

The nZEB balance diagram, Figure 19, shows the high potential of reducing heating and introducing the PV production to the building. When lighting control system introduced as well, the building almost reaches the nZEB balance line. By applying further lighting reduction method, e.g. LED lamps, nZEB is expected to be achieved.

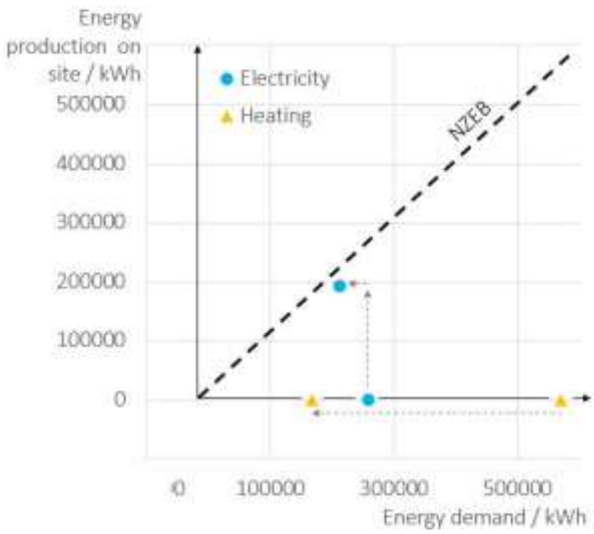

Figure 19, nZEB balance diagram with movement from initial to final case

DISCUSSION

Thermal energy demand/savings

A public building such as this has varying schedules and activity profiles throughout the year, making an assumption of a "typical day" is necessary but also a potentially misleading interpretation of the actual use and energy use of the building.

To try limit the margin of error in this case, three typical days have been chosen to represent the daily energy use profile of the building. These days have been scaled to the annual energy use and therefore have the same total annual consumption. However, when comparing these typical days to what the energy simulation tool perceives of the input data, the profiles differ notably.as can be seen in the appendix.

Technical assumptions with regards to thermal conductivity and airtightness of the exterior envelope, performance of the HVAC system were initially made to replicate the use of the building with reasonable margin of error. However, these assumptions lead to secondary sources of error in terms of potential of energy saving measures.

The thermal energy saving measures which prove to have the greatest effect are improving the efficiency of the HVAC heat exchanger and adding 100mm of interior insulation to the entire envelope, the latter of which has several accompanying issues. These include moisture safety, variations in thermal comfort and impact on environmental factors in the preformed LCA.

The moisture safety of adding interior insulation may be impacted negatively by adding interior insulation since the thermal barrier of the exterior wall is accentuated and moved closer to the interior of the building, subsequently increasing the risk for condensation in the exterior wall. A potential solution to this problem could be to have a well-ventilated air gap and a well-designed system to handle possible condensation run-off. The details and economic consequence of such a solution have not been considered. Additionally, the thermal comfort in certain zones of the building may be negatively impacted as a result of lowering the heating demand with additional insulation and may consequently give rise to a cooling demand which does not exist today. This particular effect can be observed in the operative temperature of the offices. Contrarily, the impact on environmental factors included in the LCA of adding interior insulation proves to be positive in a majority of the observed factors over a 50 year period.
Hereby, the secondary implications of altering the building's energy use, by for example adding interior insulation, are notable in terms of additional investment and energy costs and must be considered in far more detail in a full scale investigation.

Thermal energy production
To avoid over-production, the ST system studied, is dimensioned for the lowest thermal need of the building, occurring in July. The summer demand is, however, significantly lower than the demand in winter; strongly discouraging the use of ST in this building. Moreover, the LCC analysis reveals that the installation of such system is not profitable under the current prices and price change rates. Potentially, a ST system could be used for other purposes such as DHW or perhaps even to support a ST cooling system. These options would be interesting to address, but have not been considered.

Electricity energy demand/savings
Similar to technical assumption made for the thermal energy demand of the building, are the assumptions made for the electricity demand. These include installed effect and schedules of electric lighting, appliances and absence of lighting control system. With these rough assumptions in mind, the actual potential of saving electricity has been uncertain throughout the project.
An understanding of that installing a lighting control system could save up to 25% and by replacing the current lights with LED's could lower the electricity demand for lighting even further, leave a great potential for reduction of the electricity demand. However, due to the uncertainty of the initial assumptions of electricity use, the implications of such saving measures have not been considered further. Hereby, PV production of electricity serves to cover the current electricity demand only.
Further, by reducing the installed effect of lighting and appliances, the heating demand would be negatively impacted.

Electricity production
The effect of shading became apparent at an early stage, when the entire roof and parts of the southern façade were covered in PV panels in an attempt to maximize the annual production of the system. The seasonal fluctuations in production became apparent; overproducing in summer and leaving significant deficit during remaining parts of the year. This (rather expected) result encouraged a design of a PV array which would reflect the solar height and azimuth in spring and autumn, and intuitively reduce the deficit during these periods.
Parametric studies however revealed that despite improving the system design in order to produce more electricity in spring and autumn, the annual output did not improve significantly compared to covering all suitable areas on the roof. The "optimized" solution in DIVA could hereby be difficult to motivate from an economic standpoint and is more or less subject to the aesthetic preference of the client.

Economic sensitivity
Economic parameters tend to be dynamic and fluctuate depending on many socio-economic factors. The profitability of an investment hereby depends highly upon assumptions made to represent these fluctuations. By conducting a sensitivity analysis of parameters such as inflation, interest rates and

price changes rates, some of the natural variation of the factors could be accounted for in this case, but essentially, leave no clearer prediction of what the future of the investment may hold. A general trend which can be observed from the sensitivity analyses is the increased profitability at low interest rates and high energy price change rates for both ST and PV investments.
The economic iterations are further reflected in the discrepancy of buying and selling prices of electricity. The final price is dependent upon several factors which differ widely amongst grid provider and play a notable role in the price balance of the installed capacity of the system. Political incentives such as (annual) net metering and investment subsidiaries also notably alter the price balance. None of these factors are however, by any means certain in today's energy market in Sweden, for which an assumption of a "worst case scenario" seems to be the safest bet in terms of final profitability of the installations. However, this scenario would strongly discourage any smaller scale solar energy investments in Sweden.

CONCLUSIONS

The energy demand of Helsingborg's concert house is unevenly distributed, where the heating demand constitutes 68% of the total annual demand for heating and electricity. At first glance, prioritizing thermal energy production seem as an obvious and necessary to approach nZEB retrofitting. However, to prioritize thermal energy production with solar thermal collectors for this building, unfortunately turns out to be unjustifiable from an energy production, economic and environmental perspective.
Electricity production from photovoltaics proves to provide a notable compensation for the building's electricity demand, for which an investment in a PV system can be economically justified. It can be concluded that, considering the already high initial cost of roof mounted BAPV and limited improvement of maximising production in spring, autumn and winter by altering the installation's tilt and orientation, is not economically justifiable.
Moreover, if dimensioned to over-produce electricity, it is recommended to sell electricity from an installed PV system, since this shortens the payback time of the investment significantly.
Other aspects which would be valuable to consider further are LCA of PV, heat exchanger, lighting solutions and to pay significant attention to moisture safety of both energy saving measures and applying solar panels to an existing construction.
There are many aspects which motivate not altering the building at all. However, a progressive approach to solving non-standardized problems are required for an ever aging building volume.

ACKNOWLEDGEMENT

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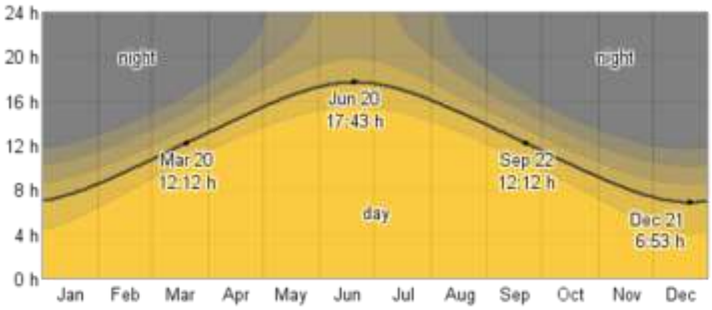
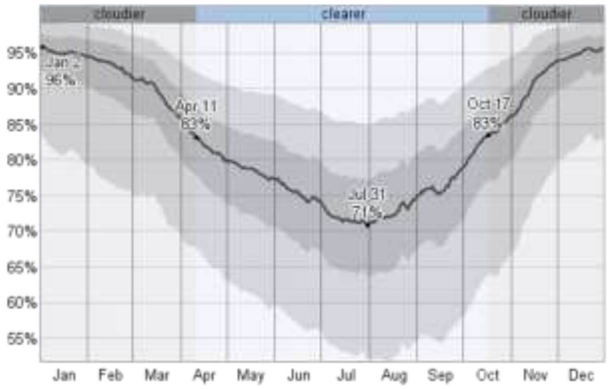
APPENDIX

Climate analysis

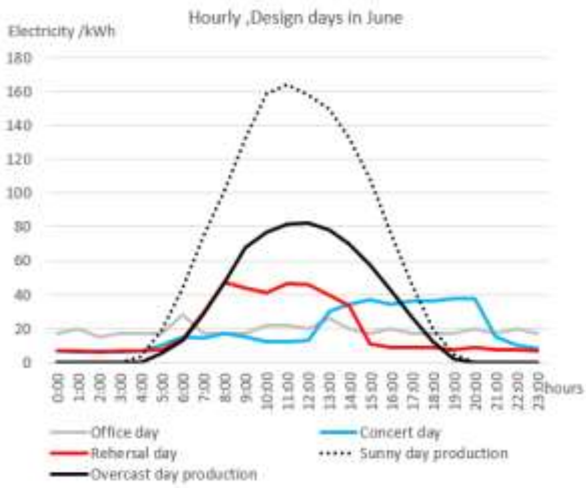


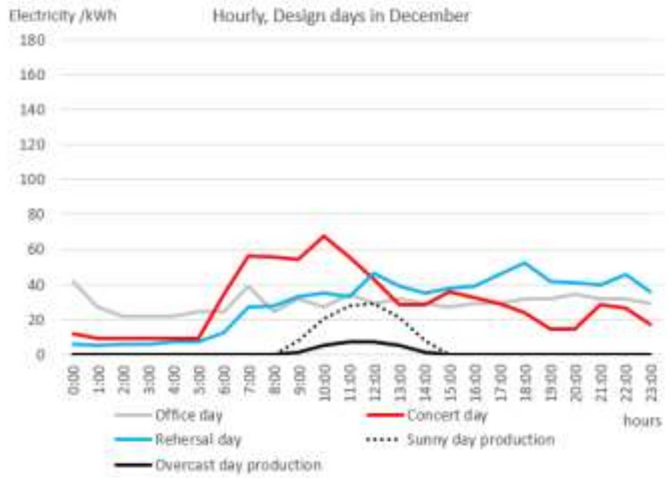


DesignBuilder settings

Construction U-value/ (W/m2-K)		**Changed settings in the parametric study**
external wall	1.423	+ 10 or 20 cm EPS
roof	0.25	0.082
slab on ground	1.800	+ 20 cm EPS
windows glazing	2.590	1.8
window frame	5.83	2.0
Infiltration / ach at n50 Pa		
building	1.6	0.6
Occupancy p/m2		
circulation	0.04	
office	0.03	
smal/big hall	1.08	
basement/ attic	0	
HVAC system		
building	VAV with HR 60% efficiency	85% efficiency
Internal gains /(W/m2)		
basement/office	3	
rest of the building	0	
Lighting/(W/m2-100 lux)		
basement/attic	off	
office/ circulation	6	
small/big hall	25	
Set point temperature (heating/ cooling) / ºC		
circulation	18-20 / 24-26	
office/ small/big hall	18-21 / 24-27	
basement/attic	0-0/25-28	

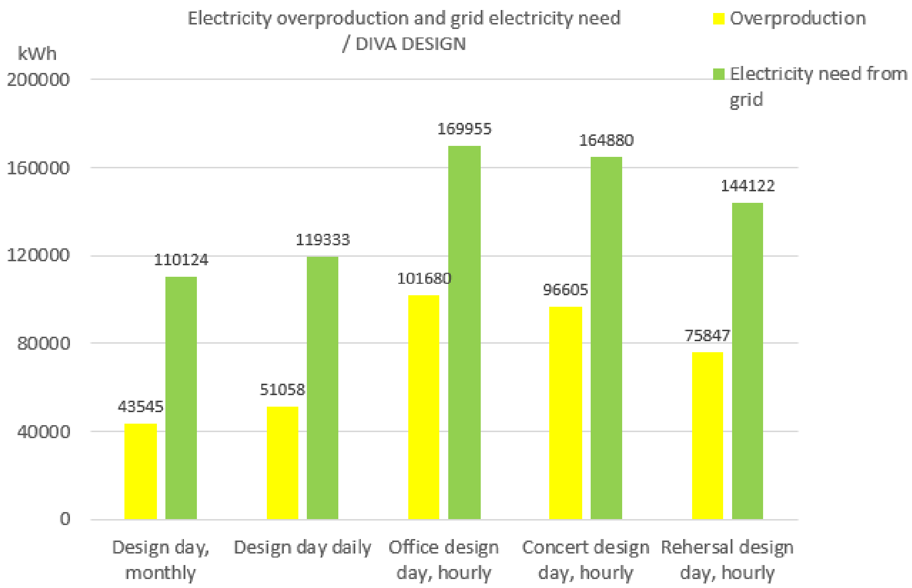
Design day, 3 type of typical days in the building



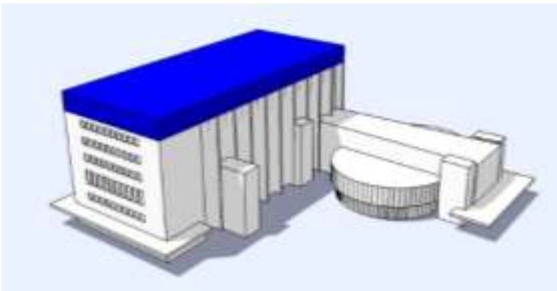


Overproduction

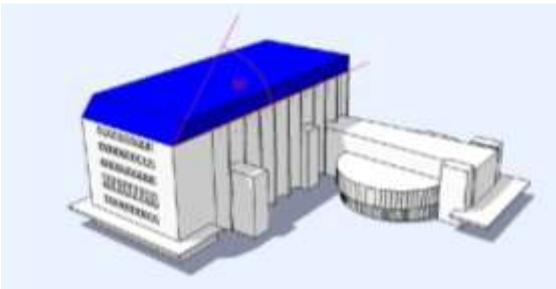
Difference in total annual electricity overproduction according to different design days

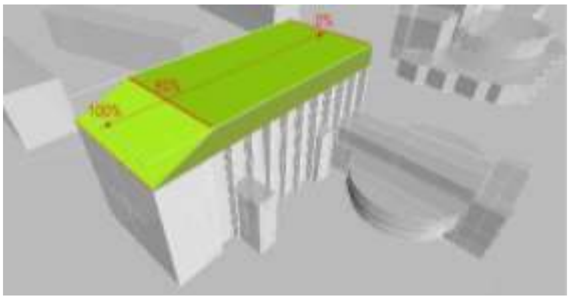


Four studied cases



Case 1. BAPV Case 2. External structure to maximize PV area

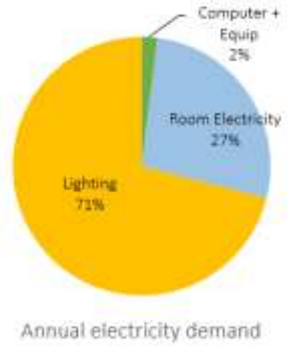


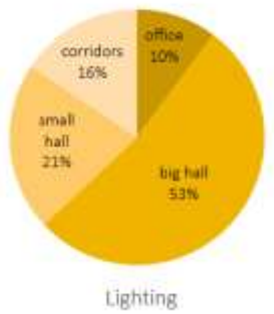


Case 3. SAM oriented solution Case 4. External structure optimized by Galapagos

Lighting

Distribution of electricity usage





Effect of control lighting in DesignBuilder