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Case study of increasing photovoltaic energy solar fraction in a conventional office building in northern latitudes

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Abstract. Current trends in planning office buildings are moving towards reducing primary energy consumption for heating, hot water heating and cooling. Availability of the solar energy resource and the low temperatures in northern latitudes from early spring until autumn provide the possibility to use photovoltaic (PV) energy for heating, cooling and other energy needs. This article calculates the heating, cooling, hot water and electricity demand of an office building with a glass facade of 65% of the total wall area. The calculated annual total energy consumption is 120 kWh m^{-2}. To reduce the heat and electricity consumption from district heating and the power network, PV modules are integrated into the roof and facade and the solar fractions of the PV energy of the four energy loads (heating, cooling, hot water, and electricity) are found. Optimization of the PV module tilt angles on the facade and roof results in the maximum solar fraction for cooling, heating, preparing hot water, and electricity consumption, 98.4%, 32.1%, 71.7%, and 51.6% respectively. For total load, the calculated maximum solar fraction is 49.8%.

Key words: solar fraction, photovoltaic, building, cooling, heating.

INTRODUCTION

Integration of photovoltaic (PV) modules in the facades of buildings has been investigated since the first PV modules were created. Since integration of solar technology modules in wall and roof surfaces is easy and cheaper compared to wind turbines, the attractiveness of building integrated PV (BIPV) technologies is still there (Shyam, 2013). The potential yields of a PV installation can be derived from the sunlight falling on the building facade. Depending on the geographical coordinates and facade azimuth, the yearly solar yields vary from 500 kWh m^{-2} to 900 kWh m^{-2} (Hussein et al., 2004, Hwanga et al., 2012). The periodically adjustable tilt angle of the PV module in cold and hot seasons has also been investigated and it has been found that changing the tilt angle could improve the quantity and homogeneity of the produced power (Mehleri et. al., 2010), but small deviations in tilt angle do not change the output power more than 20% (Santos & Rüther, 2014). Solar fraction has been investigated in Southern European conditions and it has been found that depending on building compactness, horizontally inclined modules can deliver 95% of the electrical energy and the modules integrated in the eastern facade 41% (Hussein et al., 2004). At the same time, in the case of buildings with small rooftop, but large wall area, a PV installation can cover up to 5.1% of the power consumption (Hwanga et al., 2012). For solar cooling application, it has been found that the yearly solar fraction in Hong-Kong with a PV on roof is 0.68 and with a BI PV 0.477 (Fong & Lee, 2012) – a 21% difference in solar fraction between building integrated and roof top installations. Integration into facades of buildings has shown that the efficiency of a module depends on the ventilation of the PV modules and can drop 2–3% depending on the power-temperature coefficient %/K (Clarke et al., 1996). The results of different solar fraction simulations or direct measurements are not adaptable to the Northern European weather and building demand conditions. In addition to estimating the solar irradiation falling on a BIPV of a typical office building, the solar fractions to hot water, cooling, heating and electricity have to be found separately and in total. Optimization of the PV angle on a facade considering the maximum solar fraction must be analysed in all facades and the roof together.

MATERIALS AND METHODS

Simulation of the cooling, heating, hot water, and electrical energy demand of an office building

The building surface area to volume ratio (A/V) has an important role to the cooling and heating demand of a building (Hwanga et al., 2012). A/V ratio 0.317 has been chosen that represents the typical compactness of existing office buildings in urban conditions (Eicker et al., 2013). The chosen one thermal zone building is 79 m long and 24 m wide and the total height is 9.6 m. Fig. 1.

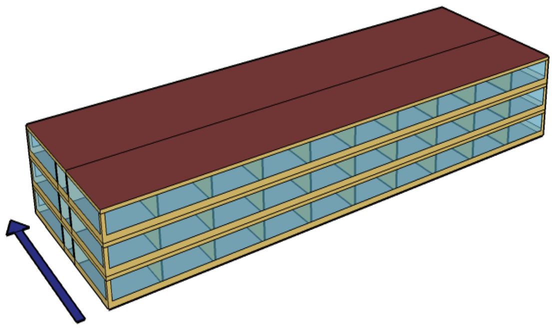

Figure 1. 3D view of the simulated office building (view from the southern facade).

The building has three floors with a treated floor area (TFA) of 5,040 m^2. The storey height is 3.2 m and the net storey height is 2.8 m. From the total volume of 18,202 m^3, the net air volume is 12,500 m^3. The total and PV installation areas (A_{tot}, A_{inst}) and glazing fractions are given in Table 1. For the thermal mass, wood based furniture is used with the volume of 300 m^3 and the specific heat capacity of 196 MJ K^{-1}.

The U-value of the external walls in all azimuths is 0.319 W m^{-2} K and the U-value of the window is 1.1 W m^{-2} K with the total solar energy transmission value (g-value) of 60% and the fraction of incident solar energy transferred through the glazing (b-value) of 40%. The solar transmittance of the internal shading devices was defined as 40%. The internal loads for lightning, equipment and people were defined as 10 W m^{-2}, 15 W m^{-2} and 5 W m^{-2}, respectively (15 m^2/per person) (Estonian Ministry of Economic Affairs and Communications, 2012). The detailed schedules of internal load profiles are different in weekdays (from 8 a.m. to 5 p.m.), Saturdays and Sundays. The schedule types selected are the default EnergyPlus schedules for light, occupancy and electrical equipment.

For the building simulation, the EnergyPlus software was used. The cooling and heating demands were simulated in Tõravere, in Estonia, at the geographical coordinates of E26°27' longitude, N58°15' latitude, and elevation of 70 m. The hourly resolution weather data generated for Estonia was used (Kalamees & Kurnitski, 2006). The yearly mean ambient dry bulb temperature is 5.74°C. The global horizontal irradiance is given in Table 1.

Table 1. Building surface, PV area and global irradiation values on the surface

		Azimuth of the vertical surface area				Roof area	Total area
		south	east	north	west	m^2	m^2
		0°	-90°	180°	90°	-	-
Total surface area	m^2	758.40	230.40	758.40	230.40	1,896.00	3,873.60
Glazing fraction	-	65%	60%	65%	60%	0%	
Installation area	m^2	265.44	92.16	265.44	92.16	1,896.00	2,611.20
Yearly global irradiation of surface	kWh m^{-2}	853.43	636.69	342.89	634.56	948.33	3,415.91

The indoor temperature is scheduled at 21°C for heating and 25°C for cooling. For cooling, a building compression chiller system with an Energy Efficiency Ratio (EER) of 2.8 is used. The EER ratio also takes into account all auxiliary devices needed to cool the building. For heating, the building ground-sourced heat pump system with a collector heating indoors is considered. The yearly Coefficient of Performance (COP) with auxiliary devices of 3.0 is used. Humidification is not used.

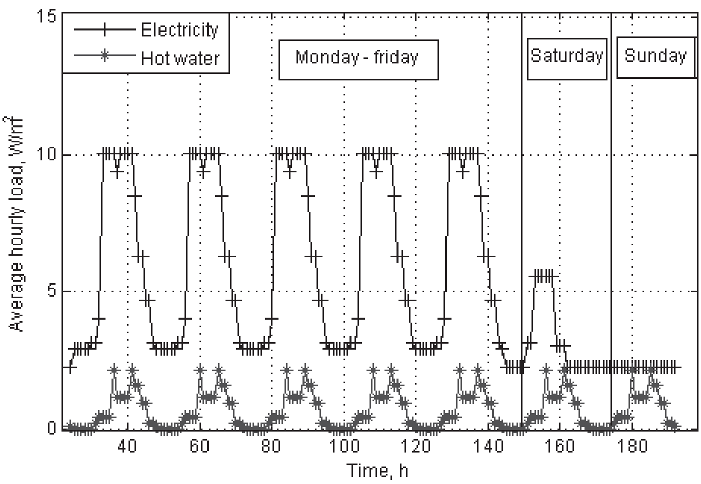

Figure 2. Hot water and electricity consumption load profiles for a typical weekday and weekend.

The hot water and electrical energy demand is dependent on the function of the building. For office buildings, different loads are given for weekdays and weekends. The yearly average hot water load is 100 litres m^{-2} and the electrical consumption

45 kWh m^{-2}. The resulting yearly total hot water load is 30.2 MWh and the electrical consumption 230.5 MWh. Hot water is heated with the same heat pump that is used for heating the building and the yearly average COP with auxiliary devices is 2.7. The maximum hot water and electricity load depends on the treated floor area of the office building. See Fig. 2. The weekly loads of hot water and electrical energy consumption are considered identical over the year.

Solar fraction calculation

For the calculation of solar yields from the building ambient air facing surfaces, the TRNSYS® simulation software and the hourly weather data in Tõravere were used. The installation surface area A_{inst} of the surfaces was taken into account for calculating the solar yields. Calculation of the solar irradiation falling on the PV modules installed on vertical surfaces was performed so that 100% of the A_{red} was used for the PV modules. As the PV modules are inclined, shading behind the PV modules occurs. Shading will be avoided if the glazing area is 60% or more and the PV modules are installed in one row placed vertically over the windows. The additional shading caused by the PV modules to the glazing was not taken into account.

On the horizontal surface (the roof of the building), the surface area of the PV modules is dependent on the tilt angle (α) of the modules. As the tilt angle increases, the pitch of the side-by-side positioned solar rows increases. Taking into account that shading of the PV modules should not occur in the period from 1 March and 31 October starting from 7A.M., the pitch in meters and the surface area of the PV modules can be calculated. When altering the tilt angle, the shaded area behind the PV modules changes. No PV modules can be installed in the shaded area. After calculating the pitch distance, the surface area of the PV module rows and the shaded area was found. In every simulation, the ratio of $A_{PV,hor}$ to the total area of the horizontal A_{hor} was calculated according to the derived equation 1.

$$R_{PV,hor} = \frac{\tan\beta}{c \times (\sin\alpha \times \cos\gamma + \cos\alpha \times \tan\beta)}, \tag{1}$$

where: $R_{PV,\ hor}$ is the ratio of $A_{PV,\ hor}$ to A_{hor}; c is the width of the PV module, α is the tilt angle of the PV module; β is the hour angle of the sun, and γ is the azimuth angle of the sun at 7A.M. in Tõravere. Multiplying the $R_{PV,\ hor}$ by the A_{hor}, the $A_{PV,\ hor}$ is found and can be later used in calculating the electrical energy produced by the PV modules. Solar fraction (P) is the percentage of the energy produced by PV modules in the building energy demand. If the energy from PV modules is higher than the demand, the residual electrical energy is forwarded to the grid. Solar fraction ratio can be calculated separately for each building azimuth surface or in total. The following equation calculates the difference between the electrical energy from PV and the load.

$$\begin{cases} \dfrac{Q_{load,i}}{\eta_{load}} - Q_{sol,i} \times A_{inst,N} \times \eta_{PV} \geq 0 \Rightarrow D_i = Q_{sol,i} \times A_{inst,N} \times \eta_{PV} \\ \dfrac{Q_{load,i}}{\eta_{load}} - Q_{sol,i} \times A_{inst,N} \times \eta_{PV} < 0 \Rightarrow D_i = \dfrac{Q_{load,i}}{\eta_{load}} \end{cases} \tag{2}$$

where: $Q_{load,\, i}$ is the energy load of the building in kWh; $Q_{sol,\, i}$ – the solar yield on one surface of the building in kWh m^{-2}; η_{load} – the COP or EER value of heating, cooling or hot water heating (electricity η_{load}=1); η_{PV} – system efficiency of the PV installation; $A_{inst,\, N}$ – installation area of the PV installation in m^2; D_i – the difference between the building load and PV energy production in kWh.

The following equation 2 sums up all the calculated hourly differences and results in the solar fraction over a one year period.

$$P = \frac{\sum_{i=1}^{8760}(D_i)}{\sum_{i=1}^{8760}(Q_{load,i})} \tag{3}$$

where P is the solar fraction of electrical energy produced by PV to demand.

RESULTS AND DISCUSSION

Building energy load

An office building is modeled dynamically in three different placements to investigate the influence of heating and cooling to the longer side of the building. The dynamical EnergyPlus building simulation provides both heating and cooling in Tõravere conditions in the period of more than 5,000 hours between September and May and between April and the second part of September, respectively. The heating and cooling do not take place at the same time. The rather long cooling period for N58 latitude is caused by the high percentage of glazing, low tilt angle of the solar rays to the glass surfaces and high internal yields. The maximum cooling demand of 277 kW is lower, then heating demand is 305 kW. The yearly cooling load is 36.6 kWh m^{-2} and the heating load is 33.17 kWh m^{-2}. The reason for the high cooling load is that outer shading devices are not used and low elevation solar radiation can heat the rooms in spring and autumn. Another reason is the high internal yields. In Fig. 3, the building cooling and heating loads and the solar yields for the longer side of the building with the azimuth of 0° (south) are given.

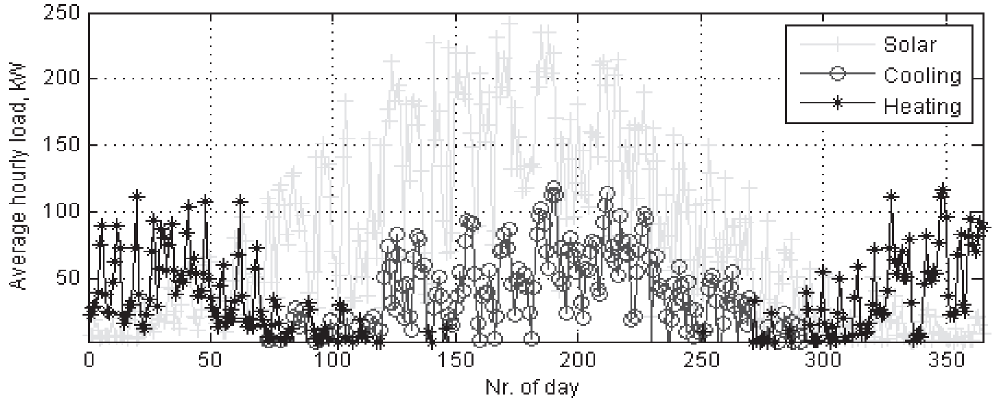

Figure 3. Heating, cooling, hot water and electrical loads and solar irradiation of the longer side of a south oriented office building.

If the building's longer side is placed to south-west or west, the cooling load is higher in the afternoon. To increase the solar fraction, shifting the cooling load towards the afternoon is more suitable as the elevation angle of the sun is high enough then for the PV array to work in the nominal power region on the modules and deliver most power for the cooling equipment. See Fig. 4.

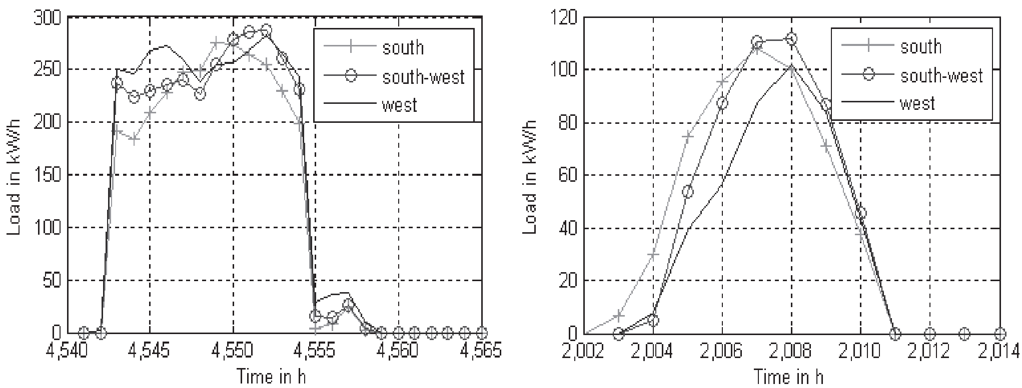

Figure 4. Hourly values of the cooling load in an average summer and spring day.

After iterating the cooling load of the building over one year period, we can conclude that for the lowest cooling load, the longer side of the building must be placed to south (azimuth 0°), if possible. See Table 2.

Table 2. Cooling and heating load maximum, mean and total values over the period of one year

	Cooling			
	South	South-West	West	
Maximum	276.97	287.12	283.74	kW
Mean	20.74	21.85	22.43	kW
Total	181.72	191.45	196.51	MWh/year
Total, per m^2	36.06	37.99	38.99	kWh m^{-2} year
	Heating			
Maximum	304.89	306.31	307.97	kW
Mean	19.08	19.55	19.86	kW
Total	167.17	171.30	173.94	MWh $year^{-1}$
Total	33.17	33.99	34.51	kWh m^{-2} year

The heating load of the building is the lowest in the case of south-oriented building placement. One reason is the low U-values of the building and the good area to volume of 0.317. Secondly, the more the house is south-faced, the lower the heating load in winter months, as solar rays rarely fall on the west and east side of the building. On Fig. 5, the influence of afternoon solar energy if a building is oriented to south can be observed.

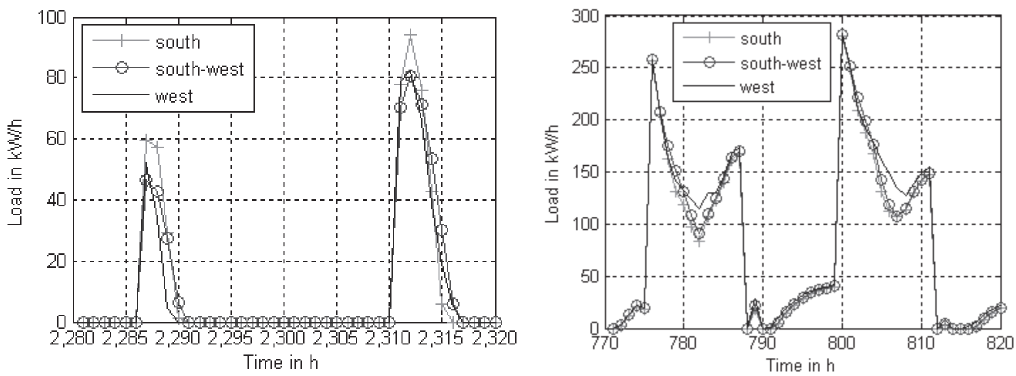

Figure 5. Hourly values of the heating load over a typical spring and winter day.

In further simulations, only south-oriented building placement is used, as this is the best case for low cooling and heating load.

Solar fraction of the facade and roof PV module installation

The solar fraction of one side of the building depending on the tilt angle of the PV modules was found. Next, the load profiles were summarized and the solar fraction angle was calculated separately for every building side. See Fig. 6. The tilts of the PV modules in the north, east, west, south side and on the roof were altered between 0° and 90°. PV module installation on zero degrees in any azimuth except on the roof of a building is difficult to implement. Shading of lower modules is unavoidable. Still, simulation for all possible angles was performed. The solar fraction increases significantly as the module tilt decreases to zero degrees. The reason is that a horizontal solar module will be attacked with the same amount of solar rays as solar panels on the roof, as shading from the wall is not taken into account. The highest altitude angle in Tõravere is N55°23’. Therefore, in further calculations, the PV tilt angles on the north, west and east facade from zero to 55° are not used, as shading by the wall should occur (Duffie & Beckman, 2006). The PV module tilt angle on the southern facade to reach the maximum solar fraction is 30° for cooling and 80° for heating. The reason is that in the case of heating, the seasonal solar altitude is low and therefore it is useful to have the PV modules on a high tilt angle. If the purpose is to get as high solar yield as possible to reduce electrical energy consumption, the PV module tilt angle must be around 40°. The reason is that electrical energy consumption has identical profile in every week of the year and in the summer months there is maximum solar energy production. The solar fraction for the roof PV module installation is dependent on the tilt angle and for all load cases the tilt angle delivering the highest solar fraction is 0°. The main reason for this is that the PV installation area can be increased as the tilt angle decreases and more power can be produced on the roof surface. For a fixed PV installation area, the optimal angle for reaching high solar fraction must be overlooked.

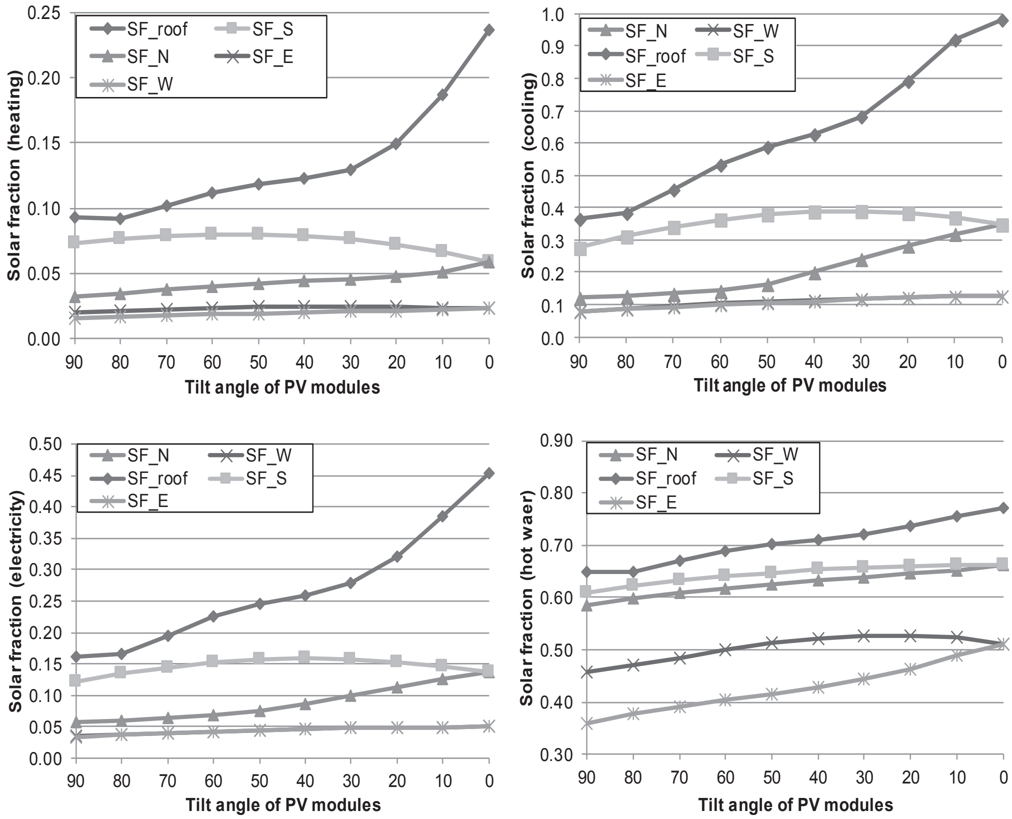

Figure 6. Solar fractions (SH) of five solar module configurations under different load profiles – heating, cooling, electricity, and hot water. Every line depicts results for north (N), east (E), south (S), west (W) facades or the roof.

Electricity produced by PV modules is used for all load types. Therefore, is important to find the PV module tilt angle when the total energy demand of the building is considered. To find the total energy demand in every time step, the loads of cooling, heating, hot water and electricity are summed up. The equations 2 and 3 were used to find the solar fraction for roof and facade installations. When PV modules are installed only on one facade of the building, the solar fraction can be as high as 10.6%, and if on the roof, the total solar fraction is 43% (Fig. 7). The solar fraction for the total energy demand is strongly dependent on how the solar yields are used – for heating or electricity, as these load types have the lowest solar fraction. In the current case, the loads are summed up and the difference between the total load and the solar yields is calculated. To increase the solar fraction of heating demand, the PV modules have to produce more energy in spring and autumn. For this reason, the PV module tilt angle for the south facade has a higher tilt, see Fig. 7. At the same time, the tilt angle cannot increase too much, as near the spring and autumn equinox the PV electricity production in northern latitudes is still low.

As the PV electricity production is related to the installation area (see Table 1) of the building, the solar fraction of the east and west facade could be higher in the case of another A/V ratio.

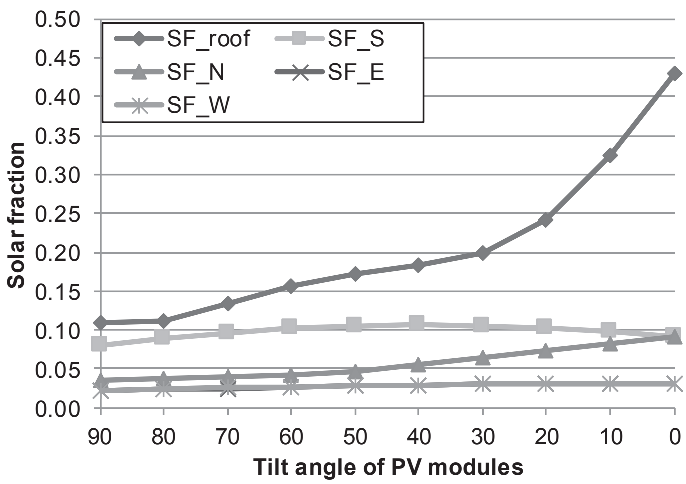

Figure 7. Solar fraction of four facades and the roof to the total energy consumption.

Maximizing solar fraction on two or more facades

In order to find the maximum solar fraction on the whole building, a parametric optimization problem must be solved because of large number of combinations. The same TRNSYS® simulation is used for this, but optimization is solved in the Hybrid Generalized Pattern Search Algorithm with the Particle Swarm Optimization Algorithm. The algorithm uses the Von Neumann neighbourhood topology with the neighbourhood size 5 and the number of particles and the number of generations equal to 10. The cognitive and social acceleration parameters are 2.8 and 1.3, respectively; the yield maximum continuous velocity and constriction yield parameter 0.6; the remaining four parameters needed for the model are the default values defined in the GenOpt® user manual (Wetter 2011, 44). Four scenarios of optimization problems were prepared. Five solar tilt angles were either fixed or limited with minimum and maximum values. See Table 3.

Table 3. Tilt angle of PV modules for four different optimization tasks

	Minimal tilt angle (maximum-90), °				
Scenario nr.	North	East	South	West	Roof
1	55	55	45	55	0
2	90	90	0	90	0
3	90	90	45	90	0
4	90	90	45	90	15

As a result of the optimization, maximum solar fraction was found and corresponding tilt angles were calculated. See Fig. 8. The optimized tilt angle did not differ from the minimum values described in table above for cooling in first and second scenario. The optimum tilt angle found in first scenario for the west azimuth was almost the specified minimum value of 58°56', and in the second scenario for south, 12°68'. The change in the minimum angle for south is explainable by the optimum tilt angle depicted in Fig. 8. The highest cooling solar fraction of 98.29% is achieved with the first scenario and the lowest with the fourth scenario 93.60%. The change in the solar fraction between the first and fourth scenario is 4.69% and this indicates that if installation of PV as described in the fourth scenario is cheaper and more suitable, then high tilt angles should be selected for the facade and low for the roof.

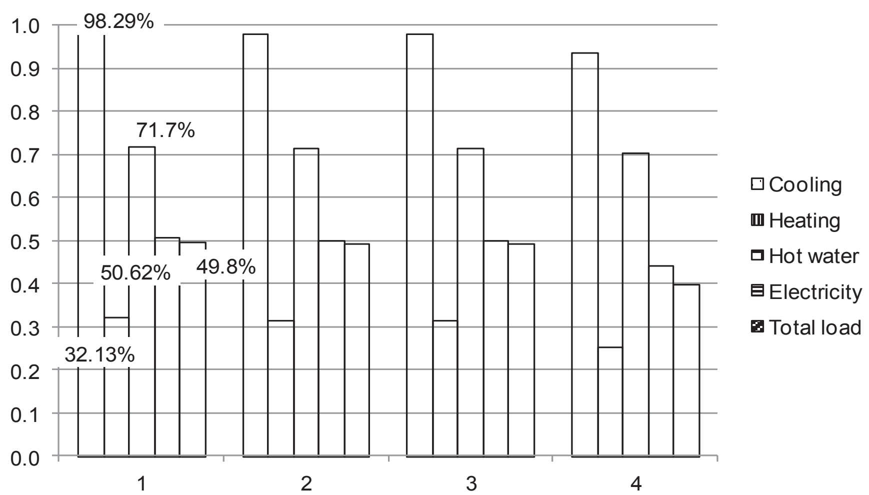

Figure 8. Solar fractions of four scenarios and load profiles.

For heating, the optimal tilt angles are similar to the values given in Table 3, but the south angle must be as high as 54°25'. A higher south angle enables to use the spring and autumn solar yields more efficiently. If the 15° tilt angle is used for the roof installation, then the optimal southern angle is 47°49'. At the same time, the solar fraction of heating drops 6.64%. The hot water solar fraction is less affected by the change in the PV installation tilt. If the PV modules on the roof are inclined from zero to 15°, the solar fraction does not drop more than 1.65%. To establish the highest solar fraction from electricity consumption, the tilt angles defined in the first scenario must be used, but using the third configuration while losing only 0.07% in solar fraction is also a good alternative. If the PV installation on the roof is inclined to 15°, then the solar fraction drops 6.42% compared to the first scenario. The solar fraction for total energy demand is similar in first three scenarios, but if the PV installation on the roof is inclined to 15°, then the solar fraction drops 9.77%, which is a significant difference in energy – 35.4 MWh per year^{-1}.

CONCLUSION

The article is a case study about the load profiles of an office building and the possibilities for reducing the energy consumption of the building with a BIPV installation in northern latitudes. The cooling, heating, hot water, and electrical equipment energy demands of a building were simulated with the dynamical simulation software EnergyPlus. The resulting yearly cooling load is 36.6 kWh m^{-2} and the heating load 33.17 kWh m^{-2}. The treated floor area was 5040 m^2 and the surface area to volume ratio 0.317. The weekly hot water and electricity loads were simulated and the resulting yearly energy consumption is 30.2 MWh and 230.5 MWh, respectively. Next, the solar irradiation, the PV installation electricity production with the system efficiency of 0.13, and the energy demand of a ground-sourced heat pump for cooling, heating and hot water heating were calculated. With an hourly step, the solar fractions of the PV installation to four different loads were found separately and finally total solar fraction of the loads was calculated. The roof installation has the biggest influence on the solar fractions as the roof has largest surface area, 1,896 m^2. The differences in the solar fractions for facade and roof installations are dependent on the type of loads. After optimization of the tilt angles of the PV modules on each facade and the roof, the maximum solar fractions for cooling, heating, hot water heating, covering electrical consumption and all the loads in total are 98.35%, 32.1%, 71.7%, 51.6% respectively, and 49.8% in total. Characteristically to a case study, the results are dependent on the building geometry. To understand how building A/V ratio and geometry affect solar fraction, further analysis is needed.

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