Enabling solar shading for power generation

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Abstract

Controls of solar shadings are commonly rudimentary in focusing only on daylight control or overheating protection. But the interests in the transparent facade are collidingly multiobjective. Heat losses and gains, view to the exterior, daylight penetration and glare are a few of them. Adding photovoltaics to these objectives bears the potential to leverage the energy bill of a building to net positive. On the other side it brings a major conflict to the overall objective of indoor environment quality, as the best yield is created with blinds always in closed position. Solar shading systems with photovoltaic require a malleable, lightweight, robust and economical technology with good performance and durability. This work proposes an integrating control system for PV enabled venetian blinds to find an optimum between overall energy performance and user comfort. Furthermore, an outlook is given on the use of artificial intelligence to find the aforementioned optimum with different control strategies and PV technologies.

Keywords: photovoltaic, shading, indoor environment quality, energy efficiency, positive energy districts

1. Introduction

As climate change is progressing and the goal of limiting the increase of the average temperature to 2°C has to be reached according to the Paris Agreement of the United Nations, 2015, Positive-Energy-Districts (PED) are getting more important with the increasing urbanisation and dense neighbourhoods. To reach the Positive-Energy Standard, building complexes must produce more energy during the year than they consume. This requirement makes it quite tricky for urban buildings with more than 3 to 4 floors, so for the sake of fairness, the approach has been adopted where dense neighbourhoods get a 'surplus' for efficient use of land and, conversely, loosely built-up neighbourhoods have to produce more. (Schneider et al., 2023).

In general, to achieve a positive energy balance, it is essential to increase energy efficiency and produce as much renewable energy onsite as possible. As the roof is often predetermined for different uses, e.g., urban gardening or other activities, it is necessary to go for innovative solutions like façade integrated- or shading-integrated PV solutions to reach the plus standard.

In this work, the impact of solar shading (e.g., venetian blinds) with PV and AI controls is calculated using a Viennese building complex to test the benefits of such blinds.

2. Angular Characteristic of PV enabled slats

Solar shading slats (e.g. venetian blinds) are used to control solar heat gains in heating and cooling periods and to provide a well daylight and glare free indoor environment. This is often a conflict between fully closing the transparent façade and letting daylight in or opening the shading while causing glare. A conventional venetian blind has a pronounced angular characteristic. A key angular feature is the so-called cut-off tilt angle to block direct insolation depending on the current solar profile angle. Depending on the solar position and the tilt angle the resulting solar heat gain coefficient (SHGC) has a high variance from 0.18 to 0.07 for a 30° elevated sun and tilt angles from 25° (measured from the horizontal position) to 65° for a silverish lamella. The daylight transmittance, given as $t_{v,dir-hem}$, decreases correspondingly from 0.25 to 0.09 (Fig 1.a).

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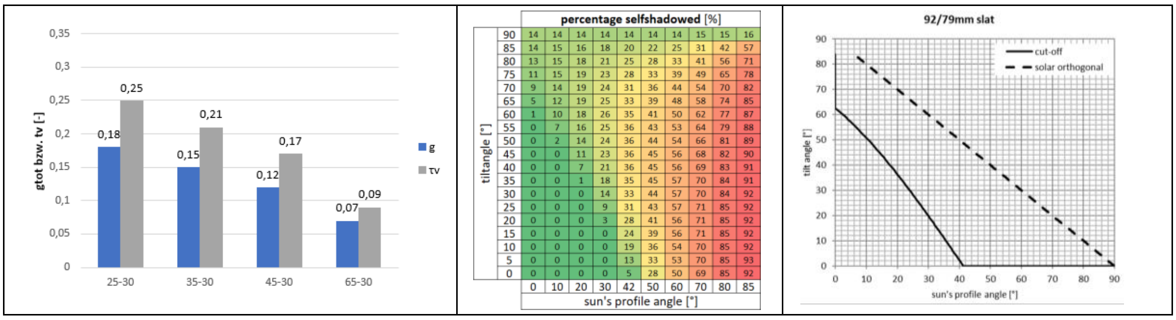


Fig. 1: (a) SHGC and visual direct hemispherical transmittance for two different sun profile angles at four different tilt angles. (b) self-shaded percentage, (c) cut-off and solar-1-axis-orthogonal tilt angle.

Enabling slats with PV adds another conflicting objective to the space of tilt solutions. The kinematic of the venetian blinds geometry results in a critical self-shadowing characteristic, i.e., the slats are very likely to shade each other when in cut-off or 1-axis-solar-orthogonal tilt function (Fig 1.b and c). Working on an hourly closed loop Tilt vs. Power optimizer, it turns out that the slats are often more tilted than would be necessary for cutting off the solar beam. Therefore, the PV yield of different lamella angles has been tested to check the self-shading coefficient. As seen in Figure 2, while in the cut-off control, each angle has been used to track the sun, in the power optimizer control, mainly angles between 40° to 90° have been used. Also, during the summer months of the cut-off control, the angle was mainly at 0°, which means that the lamella was horizontal, as the sun Zenit was too high for other angles.

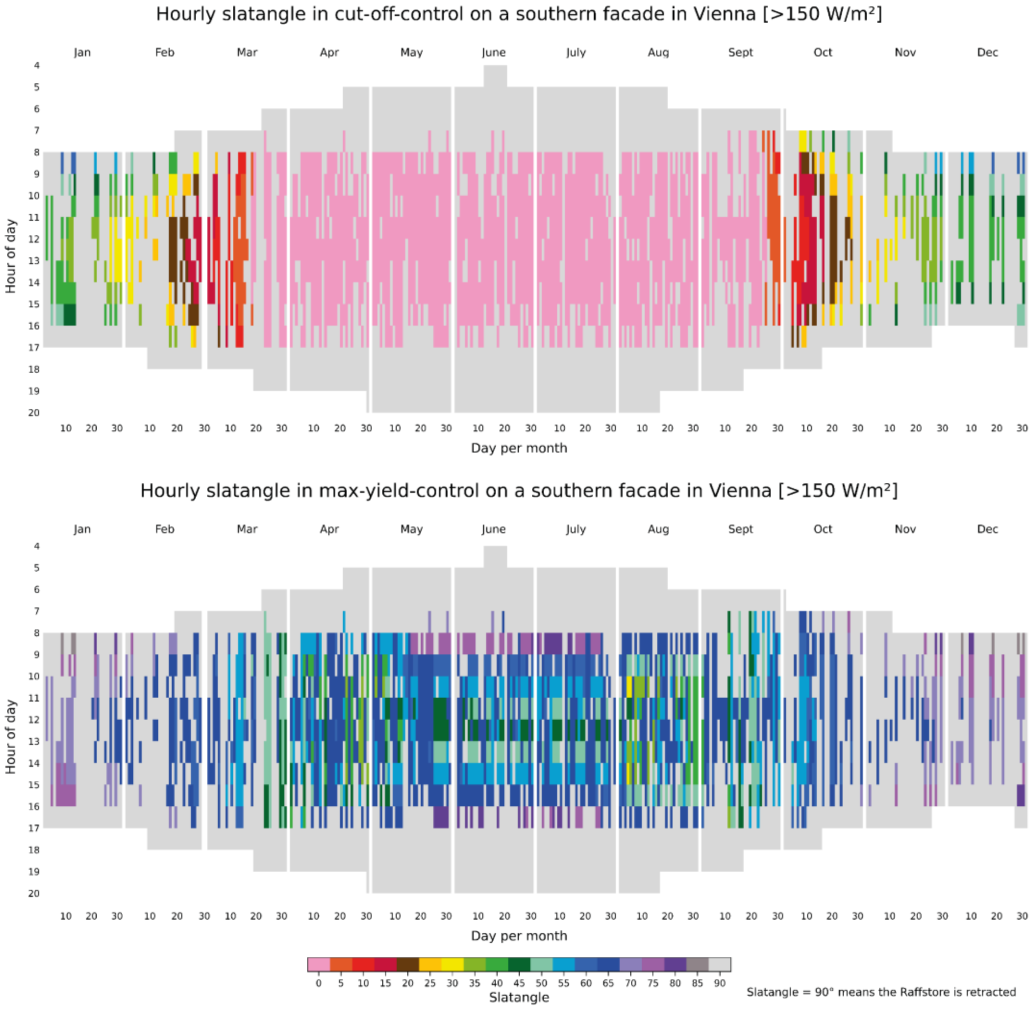


Figure 2: Optimal angles for cut-off control (top) and angles for tilt vs. power optimizer control (bottom).

Applying these angles to the lamella with integrated PV systems, the PV yield differs according to the control logic, as seen in Figure 3. While in the cut-off strategy during summer, the yield is relatively low due to the self-shading of the lamellas, in the power optimizer control, the yield remains constant during the year. Even though the angles do not change much during the yearly prognosis of the power optimizer, the yield is much higher than in the cut-off strategy. Therefore, the boundaries between the two control logics can be set as a requirement for the implemented AI to reach values between the cut-off and the power optimizer, as PV production and cooling demand should be used for the optimization.

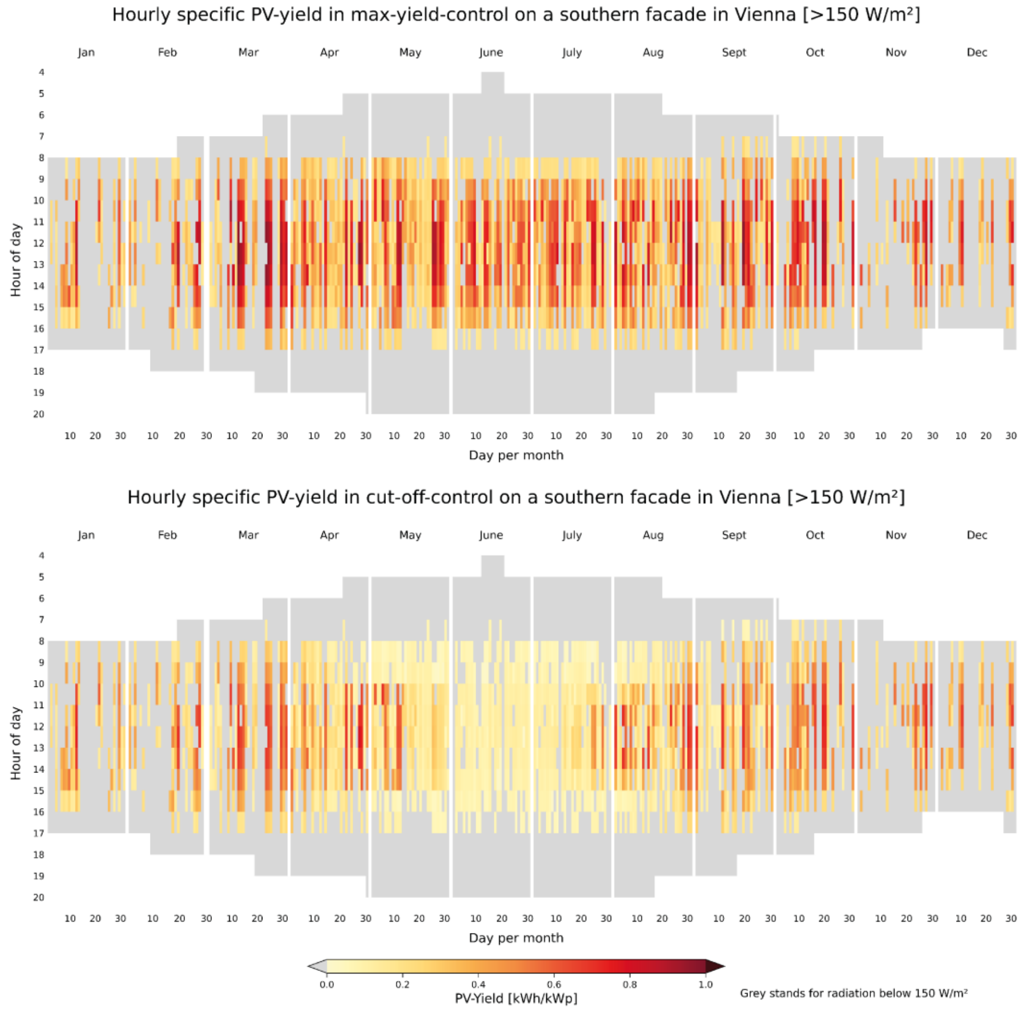


Figure 3: PV-yield for tilt vs. power optimizer control (top) and PV-yield for cut-off control (bottom).

The annual yield of the PV model in PVSites on slats (active when facade irradiance exceeds 150 W/m²), on balcony and 1-axis tracking single modules shows high variation from 422 to 727 kWh/kWp/a and a total generation of 146 kWh to 336 kWh for a 1.5x1.5 m² window respective balcony (Tab. 1).

Tab. 1: PV performance in an Austrian City, south-facing slats with 0.7 active PV surface, covering a 1.5x1.5m2 window, and a 1.5x1.5 m² balcony PV stand-alone module.

Yield	Cut-Off - Venetian Blind	Max-Yield - Venetian Blind	Balcony PV
kWh/kWp/a	422	727	678
on 1.5x1.5m² kWh/a	146	251	336

Different modules were inspected to test the efficiency of the control logic and PV-integrated shading to check the most suitable option for implementation. Therefore, tests with the modules of different angles and temperatures were made whereby the modules were heated up by the solar radiation from 20 °C to 50 °C. When reaching the highest temperature, the tilt angle of the PV system was changed, and the measurement started again. The angle was set from 0° (horizontal) to 80° (nearly vertical) and was heated up by a solar approximating light source in two-meter horizontal distance and a height difference of one meter, as shown in Figure 4. As a light source, a HL313.01 radiation matrix was used. This matrix is no standardized light source for standard testing conditions as it has a higher spectral energy in red. As the efficiency has not been measured in standardized conditions, it is not to compare with the actual module efficiency but more likely a value for comparison between different modules, which was used during the project PowerShade (Stadt der Zukunft, 2020).

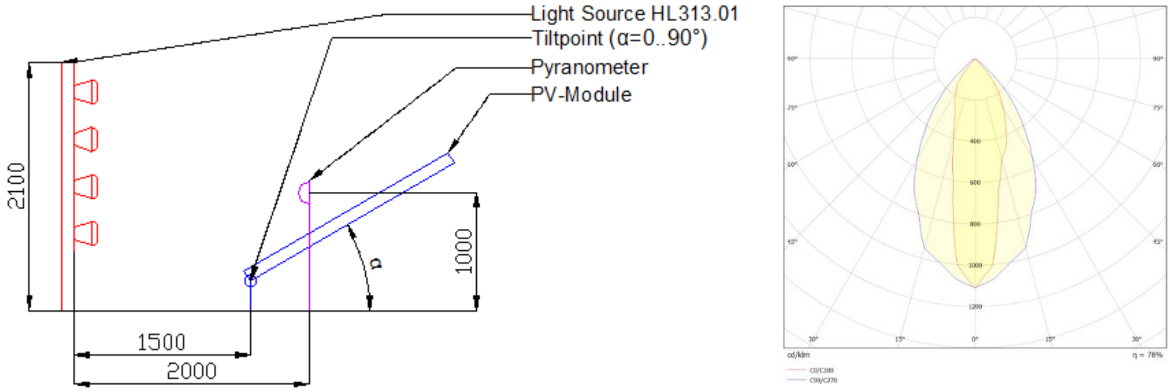
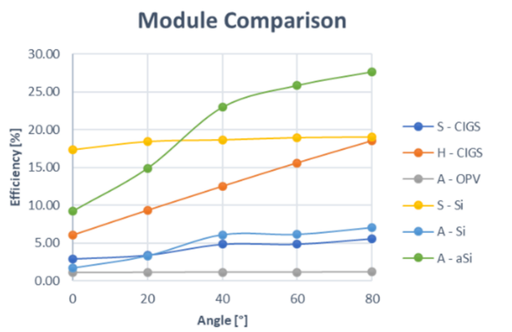


Fig. 4: Measurement setup (left) and light source radiation spectrum (right)

This setup has measured six different modules according to their efficiency decrease by changing the angle and the temperature. A comparison of the different modules is shown in Figure 5. The module names and manufacturer were anonymized, and only the first letter and the module technology were used for comparison.



		S - Si			
		Temperature [°C]			
		20	30	40	50
Angle [°]	0	0.91	0.83	0.79	0.69
	20	0.97	0.89	0.85	0.75
	40	0.98	0.90	0.88	0.78
	60	1.00	0.92	0.88	0.78
	80	1.00	0.94	0.87	0.78

Fig. 5: Efficiency degradation of different modules (left) and normalized correlation between angle and temperature of the chosen module (right)

In the case of this project, Module S – Si was defined as the most suitable option as it only has a minor angular degradation of a maximum of 10% and only a 30% reduction of the efficiency influenced by the temperature. Other modules were more sensitive to these two parameters, and therefore, not as suitable for the measurements or had lower efficiencies in general.

As shown, the maximum efficiency of the S – Si module reached about 19% at 80° inclination and 20 °C temperature. It is also shown that the module is mainly influenced by the temperature and only a little by the angle of inclination; only the angles between 0 to 40° have nearly an impact on 10% of the efficiency losses. This fits the power optimization control of Figure 2, as the control primarily uses angles between 40 to 90° to reach the highest generation efficiency.

State-of-the-art control systems of solar shadings are ignoring or insufficiently considering these angular characteristics. Advanced, deterministic methods include raytracing methods (Bueno 2016) to handle the angular behaviour and add thermal and optical data of the building, its rooms, and its surroundings for evaluating heating/cooling demands and indoor environmental quality. However, they are susceptible to uncertainties in a building's description. Our proposed methodology tackles these uncertainties. With the AI training model, the module's characteristics can be implemented in the simulation, and therefore, the control logic of the lamella angle can be changed accordingly. For example, with the selected module S – Si, the control logic can prioritize indoor comfort more. With other modules like the CIGS the angle of the lamella has a significant impact on the PV yield, and therefore, the AI has to decide whether to prioritize the production or the indoor comfort.

3. Simulation

By simulating the coupling between the building and the shading system, the connection between the cooling demand and production of the system gets clearer. For the simulation, the TRNSYS18 is used. The simulation is based on a living lab office with four workspaces. After the simulation and validating the increase and decrease of the according values, a coupling between TRNSYS18 and the Reinforcement Learning (RL) is established by including Type277 and enabling a Message Queuing Telemetry Transport (MQTT) connection between the two components. Type277 hereby couples the Outputs that TRNSYS needs for the simulation and the Inputs that TRNSYS generates by calculating each timestep via MQTT with the RL. The structure of the simulation and the parameters used are shown in Figure 6.

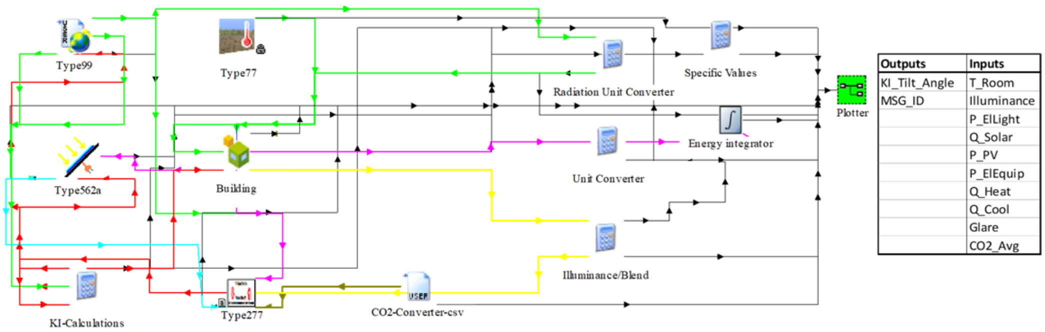


Fig. 6: TRNSYS18 simulation and used parameters

This MQTT connection was established to collect monitoring data from the testbed and compare them to the simulation results in order to validate the simulation. This methodology has also been used in other projects as, for example in the KI4HVACs (FFG, 2022) research project to compare natural environments with the training data of the AI. The implementation of the PV system on the lamella is shown in Figure 7, whereas two different modules, S – Si and S – CIGS, have been applied to the lamella to check the angle depending on yield.

Fig. 7: Application of the PV-Modules on the Testbed (left) and detail of the S – CIGS Module (right)

As the angle dependency of the modules was different, but only one lamella angle was able to be controlled, the AI was trained using the S – Si module. To validate the simulation results, the testbed has been monitored and compared to the simulation results. The measured weather data was implemented to TRNSYS via an established MQTT connection, the simulation for each timestep was done and results were compared (Tab. 2).

Tab. 2: Standard Deviation between measured and simulated values

	T_Amb [°C]	Angle [°]	T_Room [°C]	Illuminance [lx]	Glare [-]	I_Beam [W]	P_PV [W]
Standard deviation	0.8	4.0	3.0	371	0.06	28.1	2.7

The standard deviation was calculated by comparing the squared differences between the measured value in the testbed and the simulated value. The first two values, outdoor Temperature (T_Amb) and the angle, refer to Data provided by the monitored testbed. Therefore, the data of T_Amb only differs from the measured values by 2.1%. The deviation from the angle is reasonable, as the monitored data provides angles in 1° steps, but the simulation can only deal with 5° steps. Therefore, this Data deviates by nearly 9% from the original data. The room temperature (T_Room), Blend (i.e., glare), and illuminance were calculated by the simulation and fit with a mean deviation of a maximum of 36% at the illuminance. This is also reasonable, as the structure of the building, its storage capacity, and the sensor location are not exactly replicated in the simulation to make it more universal.

Therefore, the measured data from the illuminance may differ a lot. The beam Radiation (I_Beam) deviates by 2.4%, which is neglectable as TRNSYS deals with the sun elevation according to the time of day, meaning that the location and sun position are fitting for the simulation. This deviation and approximations for the PV lead to higher deviations in the PV production (P_PV) of 17.7%. Still, when checking the graphs in Figure 8, the course of the values is the same, and therefore the simulation can be used to teach the RL, as it will still be learning the exact building behaviour in the monitoring phase. Based on the experimental and simulation results, by ignoring all effective parameters and just focusing on maximizing PV production, setting a fixed lamella angle in our experiments of 50 and 60 degrees will provide acceptable PV outputs.

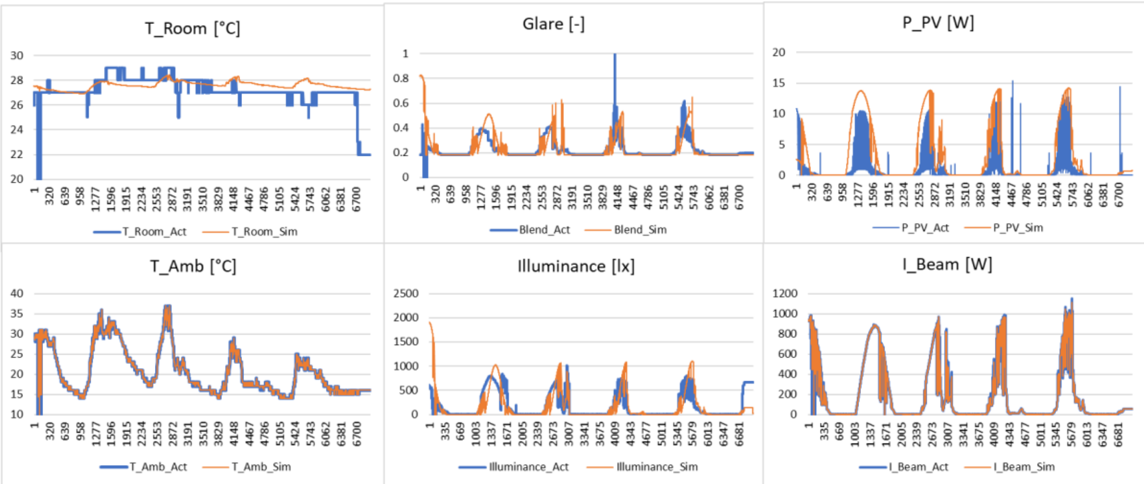


Fig. 8: Comparison of the timeseries of measured and simulated values

4. PED calculation

With the simulation results and the angular characteristics of the PV-shading system PED calculations have been made. Simulation tests have been made in order to test the efficiency increase between the cut-off strategy, the power optimization control and the AI control. The comparison was made by simulating the month June with TRNSYS and comparing the results between the cut-off and the AI control logic. In Figure 9, the comparison between the two control logics is shown.

By comparing the control logic in the middle, it is shown, that mostly the AI has higher production than the cut-off regulation. Only during the morning and evening hours the optimization control has vast differences, which decreases the efficiency by far. This may result due to the prioritized parameters of the AI, which focused on increasing the PV yield and reducing the demand for the building. Therefore, in the evening hours, the AI tried to gain as much direct energy from sunlight as possible and produce PV-power. During the course of one month, the production increased by nearly 1000 kJ (about 0.3 kWh), which resulted in an efficiency increase of 0.9% per Window (3 m²). This value is between the values shown in Table 1, which was set as a requirement for the optimization. It increases the system's overall production compared to the cut-off strategy and, therefore, could be sufficient to reach the PED status in dense districts.

To check the impact on dense buildings, the PV production increase has been implemented in the PED-calculation of a Viennese building block which is located in an outer district of Vienna and has a Floor Space Index (FSI – gross floor area divided by the area of the property) of 4.6 (Schöfmann et al., 2023). In regards to the definition by Schneider et al. (2023), this means that the building needs to produce less than the consumption to reach the positive energy standard. Due to the high density of the district still, rooftop PV is not sufficient enough to cover the demand of the building, and parts of the facades and balconies also have to

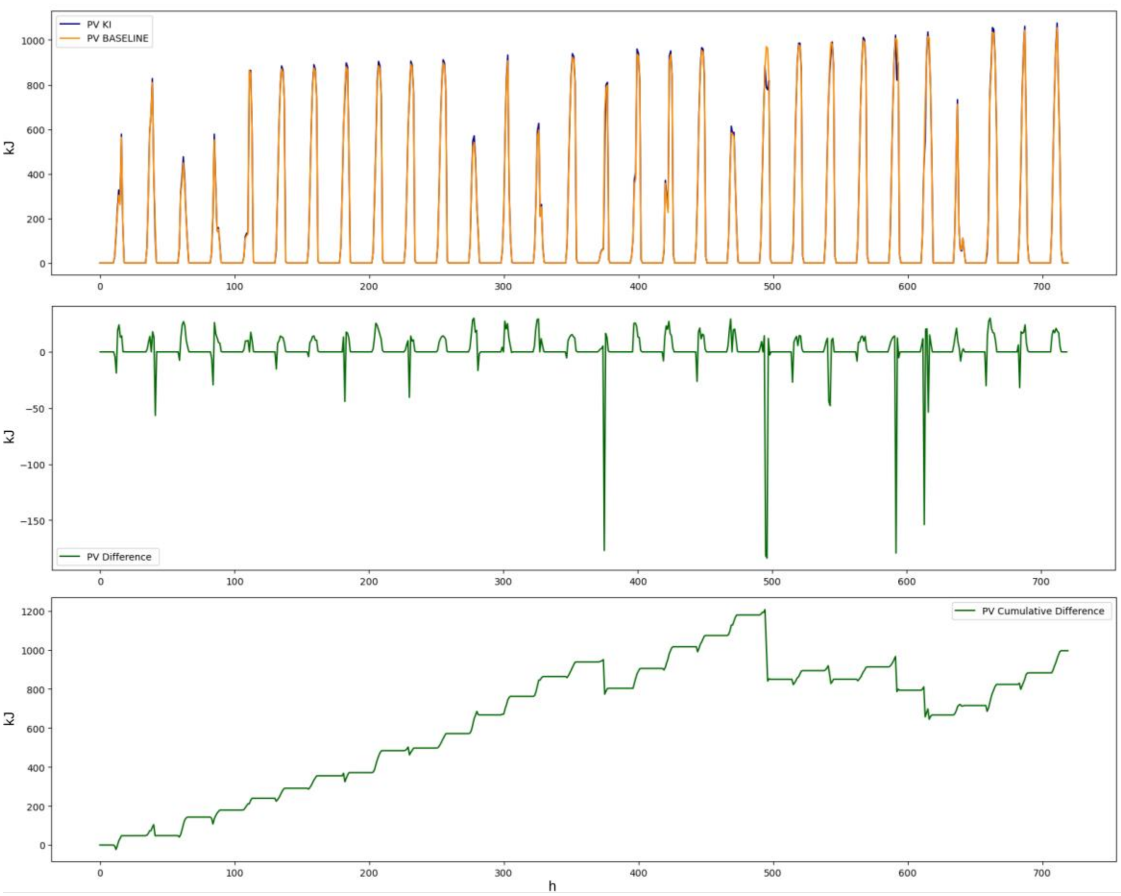


Fig. 9: Increased efficiency for regulation by comparing the cut-off with the AI control

be covered with PV-Systems. As shown in Table 1, the production of balcony PV-Systems is somewhere between the cut-off and the PV-max control logic of venetian blinds. Therefore, according to Schöfmann et al. (2023), the PED-Standard calculation has been made again by changing the balcony PV to shading systems with max-yield control logic. The power production of the PV has been calculated by scaling the maximum output of 1000 kJ/h per 3 m² (92 W/m²), as shown in Figure 9, to the window area of the buildings in south, east and west orientation from the 8th to the 3rd floor and calculating the power production with the Program PVSites. Other windows were not calculated as the shading by other buildings would be too high for economically viable production. The darker the color of the façade of each building in Figure 10, the lower the total irradiation on the surface. Therefore, the total usable window area was calculated with 1690 m² and resulted in a total PV installation of 155 kWp. In contrast, no canopy PV can be installed additionally due to the shading of the windows beneath them.

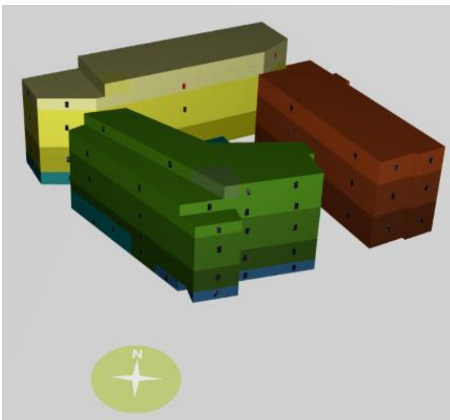


Fig. 10: Suitable areas for PV-Shading systems in the Viennese Demo District (Schöfmann et al., 2023)

This change not only influences the power production of the PV system but also decreases the cooling demand of the building as the solar gains through windows are reduced by the shading system. This results in lower demand

and higher PV production, which again positively impacts the positive energy balance. Table 3 shows the total PV installation on each surface of the building and the positive energy balance based on the net floor area (NFA).

Tab. 3: PED calculation for different control scenarios

Value	Zukunftsquartier 2.0	PowerShade Cut-Off	PowerShade Max-Yield	PowerShade AI
Rooftop PV [kWp]	482.6	482.6	482.6	482.6
Canopy PV [kWp]	68.4	-	-	-
Pergola PV [kWp]	19.5	19.5	19.5	19.5
Balcony PV [kWp]	11.5	-	-	-
Shading PV [kWp]	-	155.0	155.0	155.0
Total PV [kWp]	582.0	657.1	657.1	657.1
Total PV Production [kWh/m²$_{NFA}$a]	19.4	19.2	20.7	19.5
Primary Energy Demand [kWh/m²$_{NFA}$a]	38.0	37.5	36.5	37.3
Primary Energy Export [kWh/m²$_{NFA}$a]	2.7	2.2	2.9	2.3
Density Surplus [kWh/m²$_{NFA}$a]	40.7			
PED-Balance [kWh/m²$_{NFA}$a]	5.3	5.4	7.1	5.7

Even though the Cut-Off, Max-Yield, and AI concepts have the same amount of PV installed, they result in different balances. Whereas the production of the Cut-Off during the year is the lowest of the four concepts compared, the max yield has the highest production. This is also shown in Table 1, even if the gap is lower than expected.

The Primary Energy Demand for the three concepts has its peak with the balcony PV as the benefit of the shading system is the reduced cooling energy by reducing the solar thermal gains through summer. Again, the Max-Yield concept is the most sufficient due to the lowest demand. By comparing the Export, it can be seen that now the balcony PV has a higher output than the AI, as the highest energy production is reached during midday when the lowest demand is, and therefore, the energy can be fed to the grid.

All four concepts reach the PED-Standard, but due to the decreased demand and the increased production of the shading system with PV, the three PowerShade-Concepts reach higher values in the PED-balance.

5. Results

Today's paradigm proposes enabling every reasonable surface with PV for transforming buildings to net energy positive. We elaborated the angular effects of a PV-enabled venetian blind, put that data into a dynamic building model of TRNSYS, and coupled it with a reinforcement learning method to enhance the multi-objective search for solutions to the conflicting multi-objective problem of shading, transparent façade, indoor environment, and PV generation. Besides and still open for further research and modeling are the economic constraints for this PV application. We showed that the produced energy, the solar gains, and the indoor comfort are highly variable to different control schemes. We showed that the quality of the TRNSYS model is sufficient. While reducing the objectives to only PV generation, the TRNSYS/RL model shows that the tilt angle needs to be varied between 50 and 60° and not more.

By comparing different concepts of PV installation on a Viennese building complex, it is shown that the PV-implemented shading has higher efficiencies for a positive energy balance due to the reduction of the cooling demand and the efficient usage of sunlight during the day. When comparing the installed power with the balance, it is seen that while the installed power is increased by 12%, the production is only increased by 7%. This means that the balcony and canopy production is more efficient than the shading element. However, by considering the energy demand of the building by checking the PED-Balance, it is a gain of 34% regarding the max-yield control and 8% at the AI control. Another benefit of the AI is the increased comfort due to natural light and glare protection. In order to make a statement about the rentability of the system, an economic analysis has to be made to check whether the increased production covers the higher investment costs.

6. Acknowledgments

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Further research on the AI controls is carried out in the KI4HVACs project (No 888448), which is being funded under the 7th call of the energy research program of the Austrian Research Promotion Agency (FFG) and the Climate and Energy Fund.

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