Natural ventilation provided by a self-sufficient facade system

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Abstract. In order to meet the requirements of the European Directive on the energy performance of buildings, energy producing elements have to be integrated into the majority of the building envelopes. For integrating photovoltaic or solar thermal modules into the facade system, two different building fields have to be connected, namely the facade system on the one hand and the total building energy system, which controls the HVAC (heating, ventilation, and air conditioning) and integrates an energy storage system, on the other hand. This can result in intersection problems. One solution to overcome intersection problems can be a concept of a standalone facade system that produces energy and at the same time is able to use this energy to control indoor air climate. Thus, no intersection with other building fields is necessary. In the research of the author, a facade system is developed that uses natural ventilation to control indoor air climate. The natural ventilation is controlled automatically to overcome the risk of inadequate user control which could result in higher heating or cooling loads. The auxiliary energy which is required for the opening mechanism is provided by a photovoltaic module and a battery system. Both can be integrated directly into the facade system. This results in a self-sufficient system for natural ventilation. This paper describes the self-sufficient facade system. It contains the construction as well as simulations that are used for dimensioning the energy generating system. One part of the simulations is defining control strategies that enhance the user’s comfort and reduce heating and cooling in order to quantify the opening times and their auxiliary energy needs. Further simulations were performed to quantify the necessary capacity of the battery system. Thus, over- or underestimation of the battery capacity could have tremendous impact on the longevity, production costs, geometry, and weight of such a window. This publication compares a basic method that assumes a 6 Ah battery capacity with a detailed simulation that analyses weather data for each minute of a year. The detailed analysis suggests a battery with 50% less capacity and can halve the costs of the battery system.

1. Introduction
In 2021, all newly constructed buildings must comply to a Nearly Zero Energy Buildings standard [1]. In order to design a building that consumes minimal energy, regulation of indoor climate by self-sufficient techniques is needed. In modern buildings, the parameters of indoor climate like air temperature, humidity, and indoor air quality are often controlled through mechanical ventilation. However, mechanical ventilation requires a high amount of auxiliary energy and maintenance effort. Natural ventilation is an alternative for controlling the indoor climate that requires less auxiliary energy and has a higher user acceptance. Automated natural ventilation systems potentially lead to similar or even less heating and cooling demands compared to mechanically ventilated buildings [2]. This paper describes an automated facade system that provides natural ventilation and at the same time follows the
principles of a decentralized self-sufficient facade system. Thus, retrofitting without an intervention into the existing Building Automation System is possible, intersection problems between the facade engineering and the building services engineering can be overcome, and the foundations of the facade leasing principles can be laid. In order to design a completely self-sufficient facade system that is not integrated in the Building Automation System of a building, a photovoltaic module and a battery system would need to be integrated in each window unit. Thus, it can provide the energy that is needed to guarantee the natural ventilation. Therefore an exact analysis of the necessary battery capacity is of enormous importance. For this paper two methods were compared – one basic method and one detailed analysis. The detailed analysis is based on a simulation done by the building energy simulation program EnergyPlus.

2. Façade system
The facade system, designed as a louver window system, is an enhanced window system in terms of natural ventilation. The window is subdivided into several transparent horizontal fins, as it is shown in figure 1. These fins open completely to the outside of the room, in an angle of up to 80 degrees. With these two facts in combination with an automatically driven opening mechanism, the louver window has three main advantages to achieve a good ventilation performance and a good user acceptance: 1. The fins are opening completely to the outside so that no part of the window is protruding into the room and reducing the usable space. 2. Various small openings in contrast to one large opening area – as it would be the case with a sliding window – allow for a night ventilation, as there is a smaller risk of people, rain etc. entering the building. 3. An electrically driven opening mechanism opens up the opportunity of integrating an automated ventilation control system. For this reason, inadequate user behaviour, i.e. users manually opening the windows, will be avoided and window opening strategies that are coordinated with the actual outdoor and indoor conditions can be implemented. In summary, the louver window has a big potential to enhance indoor air quality and reduce heating and cooling loads through the automated ventilation control system and the possibility of a night ventilation.

Figure 1. Louver window system integrated in the facade of Sheffield University (© EuroLam). Figure 2. The principle of the louver window system EAL (© EuroLam).

The construction is based on the louver window system EAL from the German manufacturer EuroLam GmbH. The horizontal fins consist of insulating glazing units. These are integrated into the louver window system in form of a step-insulated glass. This leads to a structural sealant glazing appearance, which is more and more desired in fully glazed facades. The window width can vary from 40 cm up to 2.50 m. The height depends on the number of fins, with the fins’ height varying between 370 to 500 mm. The self-sufficiency is reached by integrating a PV module into one of the fins – preferably into the upper fin so that the PV cells do not lie in the shadow of the facade system itself. The
The PV module will be connected to a battery system, which will be integrated in the main window frame, as it is shown in figure 3.

The PV module will replace the outer glass pane of the insulated glazing unit (see figure 3). The integration into the construction is still in the development phase. It can be based on the thin film technology, the crystalline technology, or an organic PV system, which differ in their complexity for integration into the window and their energy output.

The PV module is connected to the battery system, which is located in the window frame. The battery system will be based on lead batteries in an Absorbent Glass Mat (AGM) system which is a low-cost solution (100-300 €/kWh) with a good recyclability [3]. The AGM technology prevents battery leakage when the window is transported and does not need any maintenance effort in contrast to a lead battery with a Redox-Flow technology. Lead batteries with a small geometry that fits into the window frame are available with a capacity of about 2 Ah and 12 volts. Depending on the field of application, two or more batteries can be conducted so a high flexibility is reached. The battery system is connected to the electric engine, a 24 volts DC system.

Figure 3. Schematic of the louver window with the integrated PV module and battery.

3. Dimensioning the battery system

The facade system should be self-sufficient. This means that the energy that is needed by the electric engine to open the window should be delivered by the facade system itself, either through the PV module or the battery system. The PV module can provide the energy during sunny days directly. During night and cloudy days, it is important that the capacity of the battery system is properly dimensioned and the energy for the electric engine can be drawn from the battery whenever it is needed. At the same time, it is important not to over-dimension the capacity as there is just limited space in the window frame for the battery system and the costs for the window system should be kept low.

When dimensioning the battery capacity for the facade system, it is important to know how much energy is needed and how long the time span is in which there may not be enough PV yield for the window opening cycles. The complexity consists in the definition of the time span, the so-called autonomy days. There is one simple method [4] to estimate the autonomy days: a defined amount of days is used only varying a winter or summer scenario and not taking into account a comparison of the energy needed, the energy produced, and the energy stored. The capacity is calculated just by the energy needed, the autonomy days and a maximum discharge depth of the battery. In the following chapters, the simple method will be described. The resulting battery capacity will be then compared to the capacity gained by a detailed analysis of the energy needed, the energy produced, and the energy stored.

To do so, first the energy needed was analyzed. This analysis consisted of a definition of the control strategy that defines the control parameters, such as indoor air quality or indoor air temperature, and their thresholds at which the window should open. Having defined the control strategies, energy simulations were done to obtain the amount of openings per day and the energy needed to provide the
openings. The energy produced was also defined using building energy simulation methods which are able to consider PV modules.

3.1. Simulation model
The investigations were carried out for an office room in a multi-story building. The room is a fictive room and was designed as a worst-case in terms of battery capacity. The room has the minimal mandatory size for 4 persons according to [5]. This results in quick increases in CO₂ concentrations. Consequently, a CO₂-based control strategy leads to the maximum number of openings and therefore to the highest energy consumption. The room is constructed in solid structure, as pre-investigations with this fictive office room showed that a solid structure in comparison to a lightweight structure results in shorter but more frequent openings in the summer months. The room is located on the ground floor, east-orientated, and surrounded above, beneath and besides by rooms that are conditioned equally. The geometry is shown in figure 4, the construction elements and the thermal properties are shown in table 1.

![Figure 4. Case study office room – floor plan and east view.](image)

| Construction Element                     | U-Value | Solar Heat Gain coefficient (SHGC) | Material and thickness of the structural element |
|-----------------------------------------|---------|-----------------------------------|-------------------------------------------------|
| External wall                           | 0.28 W/(m²K) | -                                 | 25 cm concrete                                  |
| Louver window and non-operable windows | 1.27 W/(m²K) | 0.54                             | -                                               |
| Ceiling                                 | adiabatic | -                                 | 20 cm concrete                                  |
| Internal walls                          | adiabatic | -                                 | 11.5 cm sand-lime brick                         |

The occupancy schedule is shown in figure 5 and is based on the German standard DIN 18599 as well as on the schedule for electric equipment and lighting hours. The internal heat gains for people, lighting and electric equipment are shown in table 2. The PV yield, one of the main parameters in dimensioning the battery system, depends on the climate conditions and on the opening cycles as the PV module is integrated into one of the operable fins. The simulation uses the German Test Reference Year (TRY) from 2017 for Wiegendorf, a town in central Germany. The TRY uses a synthetic year.
which represents the average climate conditions for a specific region. The average climate was defined by analyzing the air temperature and the global horizontal radiation between the years of 1995 and 2012.

3.2. Control strategy for natural ventilation

Control strategies define ambient conditions and the thresholds at which the automatic, electrically driven engine opens the window. The chosen parameter of ambient condition and the threshold which induces the opening have a major impact on the building’s energy efficiency and the users’ comfort. For example, a control strategy that monitors the indoor CO₂ concentration as a chosen parameter of the ambient conditions improves the indoor air quality while reducing the incidence of the sick building syndrome [6] but it can lead to higher heating loads if the window opening time is too long. Accordingly, temperature as a chosen parameter of the ambient condition can minimize cooling loads. Therefore, a detailed analysis about the control strategy is needed.

Various analyses have shown that passive cooling via natural ventilation can effectively reduce cooling loads [7] [8] [9]. When combined with indoor air quality control, the full potential of natural ventilation can be exploited. The self-sufficient facade system will use this combined strategy. In order to reduce cooling loads, the window will open when the operative indoor air temperature is above 25 °C and the outside temperature is more than 3 Kelvin below the inside air temperature. The window will stay opened until the operative inside air temperature drops under 22 °C. During non-occupancy time, natural ventilation will be available between 23 °C operative inside air temperature (if the outside temperature is more than 3 Kelvin below the inside air temperature) and 18 °C operative inside air temperature.

The thresholds of the indoor air CO₂ concentration are based on category II of the European Standard DIN EN 15251 [10] and on analyses of the energy efficiency of different thresholds. The European Standard DIN EN 15251 [10] defines an indoor air CO₂ concentration of 500 ppm above the outside CO₂ concentration as a threshold for buildings with moderate requirements. Supposing an outer CO₂ concentration of 400 ppm, the upper threshold for the window opening is defined as 900 ppm. The lower limit for the CO₂ control has two defining parameters: The first one is given by the constraints from the simulation program EnergyPlus in which the lowest timestep is one minute which results in a minimum opening time of one minute. The second one is given by the prevalent CO₂ concentration in the room. The lower limit for the CO₂ concentration was defined to minimize heating and cooling loads. For a town in central Germany, building energy simulations with the program EnergyPlus were carried out in order to get the most energy efficient control strategy. For a 32 m², 4 people office room equipped with a 2-m-wide and 1.58-m-high louver window, a limit of 800 ppm (strategy D in figure 6) was found to be the most energy efficient strategy for November to February (see figure 6). For the rest of the year, different lower limits did not show much difference in the energy efficiency of the building. According to these results and taking into account that a lower limit of 800 ppm – which leads to the highest number of opening per day – will represent the worst-case for dimensioning the battery system, 800 ppm is defined as the lower limit.
3.3. Comparison of the energy needed and the energy produced

The energy needed can be calculated when the number of openings per day is known. The openings per day are defined by using the described building energy simulation model in EnergyPlus. The simulation showed that the openings per day vary from 1 to 29 (Zero was not counted) with 23 openings per day being prevalent during the year (see figure 7).

The energy needed is calculated in accordance with the electric engine. The power consumption of the electric engine in turn depends on the type of louver window. For the analyzed window type, an electric engine with a power of 38.4 watts is required to open the fins. The engine needs 40 seconds for one opening. Therefore, one opening and one closing results in a power consumption of 0.43 Wh each.

The calculation of the produced energy assumes a PV module with a nominal power under Standard Test Conditions (STC) of 145 watts with an efficiency of 13.8%. The calculation of the PV yield takes into account conduction losses, conversion losses, and mismatching losses, in total 24% of losses according to [4].

First, it was investigated how the window performs if no battery is used and the produced energy has to be used directly for the window openings. Figure 8 shows that most of the days there is a lack of around 0.43 Wh, which corresponds to the energy needed for one opening. At the same time, there is a

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**Figure 6.** Comparison of the energy efficiency of 4 different ventilation strategies in a south-oriented office room.

**Figure 7.** Amount of openings per day and the amount of days per year of these openings for a fictive 4 people office room in Wiegendorf, Germany.
surplus of energy throughout the whole year. This shows that a battery system is unavoidable, as the energy produced is not always available when it is needed.

![Figure 8. The difference between energy produced and energy needed calculated per minute.](image)

3.4. Defining the battery system’s capacity

The state of the art utilizes a method to calculate the battery capacity using a given number of days during which the battery must guarantee the system’s functionality in the absence of PV yield [4]. This simple method does not require a time-consuming and detailed analysis throughout the year that compares PV yield, energy consumption, and battery charge condition and could therefore result in an over- or underestimated battery system. For a self-sufficient facade system, a precisely dimensioned battery system plays an important role, as there is no intention for external power supply and the geometrical dimensions of the battery system have to fit into the window’s frame. In the following, the battery capacity will be estimated using the simple method. The data will then be compared to a detailed analysis over the course of a year. Thus, a statement can be made whether a detailed analysis to determine the battery capacity is required or whether the simple method will be sufficient.

According to the simple method [4], there should be 3-4 autonomy days in summer and 5-6 autonomy days in winter. The occurrence of the highest number of openings together with the least PV yields help to determine whether winter or summer was the worst-case scenario. In summer, the difference between inside and outside temperature is lower than in winter. Therefore, once the window is opened, it has to remain opened longer. This reduces the number of openings in summer. At the same time, the PV yield is higher in summer. Therefore, the summer scenario will not be the worst-case scenario. The capacity will be dimensioned according to the winter scenario, accordingly 5-6 autonomy days. 5 autonomy days are defined as a working week consists of 5 days. The capacity is calculated according to the following equation as described in [4]:

$$C = \frac{W \times A}{0.7 \times U}$$

where $W$ defines the daily energy consumption, $A$ the amount of autonomy days, $U$ the system voltage and 0.7 takes into account the estimated maximum discharge depth of 70% as lead batteries should not be discharged totally.

$W$, the daily energy consumption, is defined according to the most prevalent openings per day throughout the year, as described in Chapter 3.3 (23 openings), and the energy needed per opening and closing, namely twice 0.43 Wh. This results in a daily energy consumption of 20 Wh per day. Taking into account 5 autonomy days and a system voltage of 24 volts, a battery capacity of around 6 Ah is required according to the simple method.
The detailed analysis uses additionally the calculation of the PV yield which is based on the simulation model described in Chapter 3.1. The PV yield is compared to the energy consumption per minute throughout the year. If the PV yield is higher than the energy consumption, the electric engine draws its energy from the PV yield. The rest of the energy is stored in the battery system until the capacity is reached. This analysis takes into account 24% of PV yield losses, namely conduction losses, conversion losses, and mismatching losses. In figure 9, the results are shown for a typical year. This detailed analysis shows that a capacity of 3 Ah is sufficient to cover all the energy needed throughout the year without reaching a discharge depth of more than 70%. It gets clear that just once in the year, namely in December, the charge conditions drop for 24 hours under a discharge depth of 50% (1.5 Ah). This means that although the capacity was halved compared to the capacity gained through the simple method, the battery charge condition is above a critical discharge depth of 70% throughout the year and that a discharge depth above 50% is reached every day of the year except for 24 hours in December.

![Figure 9. Battery charge condition analyzed per minute.](image)

4. Conclusion and outlook
A facade system that improves energy efficiency and reduces the risk of sick building syndrome via automatically controlled natural ventilation can be designed as a self-sufficient system. An integrated PV module and a battery system are able to provide the energy for the electrically driven opening mechanism. The analyses for determining the battery’s capacity showed that detailed simulation comparing minute-by-minute the energy produced, the energy consumed, and the battery charge condition could halve the battery capacity compared to a simple method for determining the capacity. However, the detailed simulation is based on various assumptions and constraints. The meteorological data, which is used in the simulation, does not represent a worst-case year in terms of solar radiation, as worst-case years in Germany are only available in terms of outside air temperature. The number of openings per day is highly dependent on the natural ventilation model. To determine a highly accurate simulation model, experimental studies should be done. Likewise, experimental studies can improve the results of the PV yield as the cell temperature for the PV cells integrated into an insulated glazing unit could not be taken into account.

Acknowledgement
The project on which these results are based was supported by the Free State of Thuringia under number 2016 FE 0139 and co-financed by European Union funds within the framework of the European
Regional Development Fund EFRE. The authors are grateful to the German louver window manufacturer EuroLam GmbH for their cooperation in the research work.

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