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Evaluation of on-site PV-based electrical energy production: a case study

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Abstract

For sustainable electric energy supply, the on-site production with photovoltaic systems can be a possibility. For this purpose, it is important to evaluate the potential based on the location, the technical solutions, and also the economic aspects. The present research analyses all those factors for a case study based on a commercial building in Vienna, Austria. In a first step, the energy consumption of the facility was analyzed in detail. Based on the outcome, different cases for optimization and retrofitting were developed. Different scenarios for the installation of PV-systems were evaluated via simulation, covering different fractions of the electricity need and considering the usage of local electricity storage (battery). The results show that using PV systems for covering the base load is more economically convenient and, when also retrofitting of lighting system is considered, interventions to the most inefficient parts are preferred to those to the whole system. Moreover, it was demonstrated that, due to current Austrian practice regarding pricing of PV-generated electricity, overproduction does not pay off, even though it has the potential to reduce the CO_2 *emission of buildings.*

Keywords - PV sizing, energy simulation, payback calculation, light retrofitting

1. Introduction

Among renewable sources of energy, photovoltaic is currently one of the fastest growing in the industry. In 2014, the global photovoltaic capacity rose to around 177 GW, which is about 1 % of global energy demand [1]. Rooftop- and building-integrated systems are characterized by a total of 5 to 10 kW power plant energy production for residential and hundreds of kilowatts for commercial systems [2]. Photovoltaic systems are also economically sustainable: for example, assuming an annual solar irradiation of 1000 kWh m^{-2} a^{-1}, the payback time for PV-panels can be around three years depending on the technology used. Indeed, investment costs dropped from 76.67 \$ W^{-1} in 1977 to 0.74 \$ W^{-1} in 2013 and further improvements are expected [3]. According to Swanson's Law, the price of PV panels tends to drop 20 % every doubling of cumulative shipped volume, so at present rate it halves every 10 years [4].

Moreover, from the perspective of economic sustainability, the reduction of energy demand can help to decrease the overall investment cost, e.g., by improving the efficiency of lighting and lighting control systems. Recently, a number of relevant studies has been published. For example, Richman *et al.* [5] studied 141 sample spaces and found that occupancy-based control can lead to savings between 3 % and 50 % for offices and 73 % to 86 % for restrooms. Dimming control-based on daylight level, on the other hand, can lead to savings between 9 % and 50 % [6]. Aman *et al.* [7] conducted a comparative analysis of domestic lighting lamps (DLLs) and underlined the significant improvement of LED lighting performance, leading to the continuous reduction of LED costs.

In this context, the present paper shows the results of a case study done for a centre for physical medicine in Vienna, Austria. Healthcare facilities are responsible for a considerable amount of energy consumption in non-residential buildings [8]. The requirements and the utilization of these buildings vary significantly compared to other buildings. For the purpose of the study, different design alternatives to reduce the power demand of the building by means of on-site PV generation and refurbishment of the lighting system were evaluated.

2. Method

This study focuses on a private centre for physical medicine in Vienna, Austria. The facility occupies approximately two thirds of the ground floor on the east side of a 20-year old building in the 21st district of Vienna. The centre is divided into two main zones. The first one consists of a waiting area, a reception, two offices, three bathrooms, laundry, a private area for employers, a storage space and technical rooms. The second zone is the therapy area and consists of several cabins and rooms for specific treatments (e.g., hydrotherapy, lymph-drainage), two bathrooms, and three gym rooms. All exterior walls of the therapy area feature windows, but due to privacy issues, shades are always lowered and lights are on during the entire day.

In order to determine the facility's electrical energy demand, the bills from the energy suppliers for the year 2009 to 2011 were analysed and the electricity meters were monitored for 2 months. Additionally, a survey on all equipment (lighting, computers, medical equipment, etc.) was conducted. Fig. 1 reports the results for lighting devices. Furthermore, occupancy was recorded and patient data (type of treatments, time of visit) collected for a period of 6.5 months.

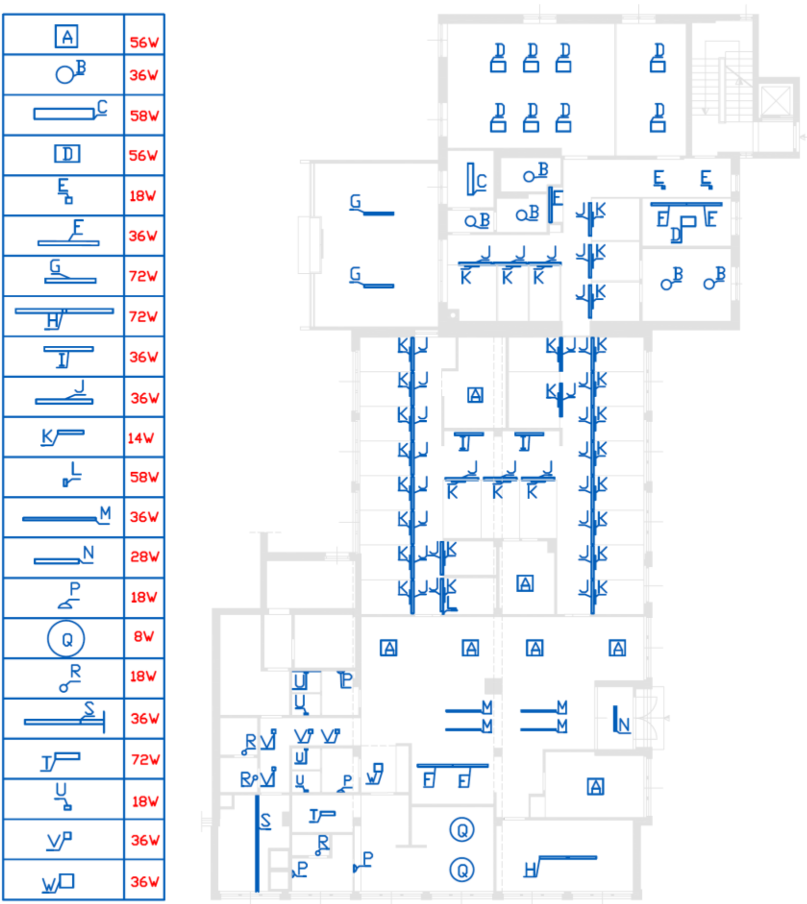

Fig. 1 Distribution of lighting devices in the Centre for Physical Medicine in Vienna

The mean annual electricity consumption for the years 2009 to 2011 was 50.8 MWh (Table 1). Fig. 2 shows the monthly consumptions. Fig. 3 depicts the mean daily profile for a weekday, generated from the data collected from meter monitoring. It can be observed that electricity consumption during unoccupied hours is around 1.4 kW while the peak load is almost 13 kW. During occupied hours, the level rises significantly and also shows peaks which are due to the operation of washing machine, drier and medical therapy equipment.

Table 1 annual electricity consumption

Year	Annual electricity consumption [kWh]
2009	45 951
2010	53 514
2011	52 966
mean	**50 810**

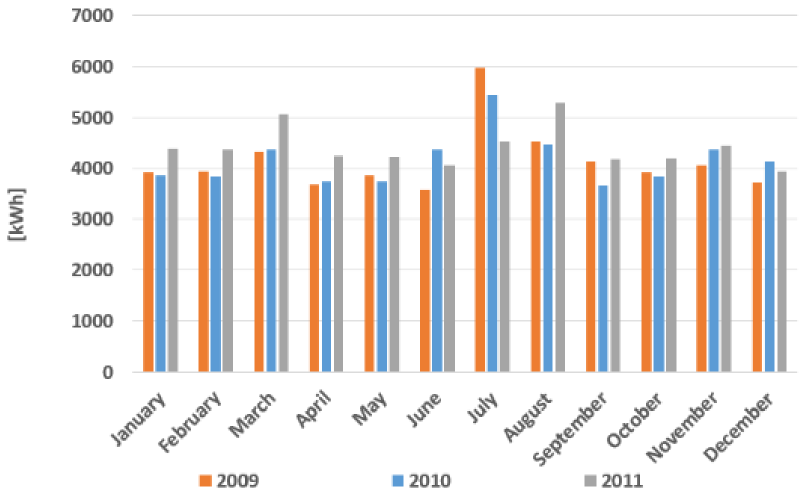

Fig. 2 Monthly electricity consumption

In order to investigate the effectiveness of PV panels in terms of energy production and also in terms of cost efficiency, different scenarios for PV implementation have been developed. For this purpose, a 3D model of the entire building has been created (Fig. 4), including all obstacles on the roof (e.g., air conditioning roof-top units and parabolic antennas) and around the building (e.g., trees and other constructions). The entire area of a roof surface has been considered for implementation of photovoltaic system. Shadings distribution during the winter solstice have been studied in order to define the proper distance for collectors with all possible slopes and orientations compatible with the roof shape (i.e., horizontal, south-oriented, east and west-oriented ones). EnergyPlus [9] with Perez model has been used to simulate hourly solar radiation incident on the collectors' surface using the Vienna IWEC weather file.

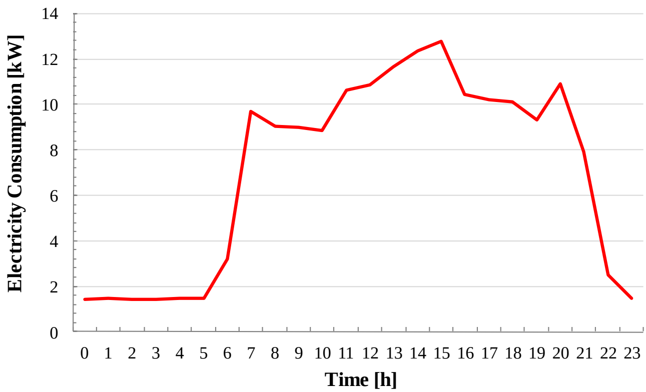

Fig. 3 Mean daily electricity consumption profile for a weekday

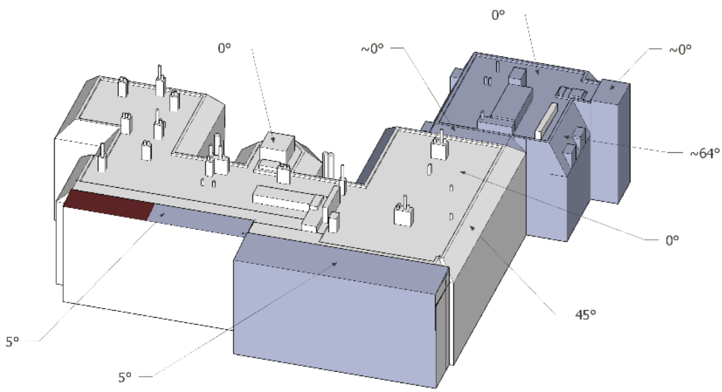

Fig. 4 3D model of the building

Poly-crystalline PV modules (1956 mm x 988 mm x 45 mm) with standard peak power of 305 W_P and efficiency of 15.8 % have been chosen. Regarding inverter and electrical equipment efficiency, a simplified constant value of 90 % has been used in calculations. Number, slope and position of the PV systems have been preliminary designed to match the power consumption profile. In this regard, constraints about energy production have been considered: according to the Austrian law [10], indeed, PV electrical energy surplus has to be sold to the electrical grid or stored.

In order to meet the demand of the 50.8 MWh/year, PV system has to be designed with a power of 48.2 kW_P. Four design alternatives have been analyzed:

1. PV system satisfying the annual electrical energy demand (i.e., 48.2 kW_P);
2. PV system satisfying only 50 % of annual electrical energy demand (i.e., 21.7 kW_P);
3. PV system satisfying only 25 % of annual electrical energy demand (i.e., 11.3 kW_P);
4. PV system satisfying only the base load (i.e., with 14.6 kW_P installed), without power sold to the electrical grid.

Three further scenarios have been considered for the first design alternative: the installation of batteries storage systems with 80 % efficiency [11] and capacities of 5 kWh, 10 kWh or 15 kWh. It has been predefined that electricity is exchanged with the electrical grid only in case of over or underproduction. Fig. 5 shows the model of the roof of the building equipped with the maximum number of PV panels possible.

Fig. 5 Roof of the building equipped with the maximum amount of PV panels

Additionally, in order to optimize the energy demand, the refurbishment of the current lighting system was considered. In a first step the existing lighting system was investigated. For this purpose, inspections on-site have been performed to collect all data about luminaires' position, ventilation system pipes and other objects affecting the performance of indoor lighting system, as well as surface optical properties (e.g., colours, smoothness). These data were used for generating a 3D model in DIALux environment. Two scenarios ("as is" and "optimized") were designed and evaluated. The "optimized" case was designed according to EN 12464-1 [12] standard that defines the illuminance levels required in healthcare facilities. Although this leads to an increase in illuminance levels in some areas, the overall consumption decreases from 4302 W ("as is" case) to 3861 W ("optimized" case with fluorescent lamps) and even to 2510 W with more efficient lighting equipment ("optimized" case with LED). Furthermore, in order to use daylight in a more efficient way, the effect of etch window films instead of blinds, dimming systems working with illuminance sensors, and occupancy controls were simulated. In particular, two alternatives have been studied: refurbishment of the lighting system applied to the whole centre or just to the therapy zone. Annual energy consumption has been computed using the IWEC Vienna weather as boundary conditions [9].

Subsequently, an economic analysis was performed by means of Net Present Value (NPV) and payback time. Investment length has been set equal to 25 years according to Austrian convention [14]. Inflation of 2 % and interest rate of 2.7 % have been taken as averages during the period from 2009 to 2014 [13]. The electrical energy price increases by 0.180 €/kWh per year, for purchase, and by 0.115 €/kWh per year for selling [14]. The PV installation cost has been assumed equal to 1900 €/kW$_P$ [15] and the corresponding Government incentives are equal to 200 €/kW$_P$ [14]. Residual values have been accounted, considering a linear value loss. Maintenance and assurance annual costs have been assumed equal to 0.4 % of the investment cost [15]. The inverter is expected to be changed after 13 years, with a cost of 126 €/kW$_P$ [15]. The storage system, if applied, has an installation cost of 1000 €/kW [11], without additional maintenance costs.

For the refurbishment of the lighting an investment cost of 3260 € for LED lamps is expected. The costs for installment were considered according to EUROSTAT [13]. Occupancy sensors cost was estimated 40 € per piece, while dimming and lighting sensors systems 220 € [16, 17]. The cost of opaque film for windows has been estimated equal to 19.7 €/m^2.

3. Results and discussion

Results regarding both the installment of PV panels and the LED lights are reported in Tables 2 and 3. It can be observed that with the decrease of the PV power installed, the NPV decreases as well. The same can be said for the payback time, that was also notably decreased. A storage system was found to be less convenient. The refurbishment of the whole lighting system of the healthcare centre makes the investment less attractive because of the much higher initial cost. On the contrary, the partial refurbishment solution brings the NPV to an increase of 30 %, with respect to the case without refurbishment, and a decrease in payback time of 2 years.

The results show annual electrical energy savings of 74.6 % and 72.4 %, respectively, for the first and the second design alternatives. These two refurbishment solutions have been coupled with the first PV system design in the economic analysis.

Table 2 Results of the economic analysis regarding the installation of PV

PV [kW_p]				**Storage [kWh]**			**Initial investment**	**Annual en. expence**	**NPV**	**Pay-back time**
Peak (48.2)	50 % (21.7)	25 % (11.3)	Base (14.6)	5	10	15	[€]	[€]	[€]	[yy]
X							81 923	1 690	42 550	15
	X						36 814	5 393	25 931	13
		X					19 185	7 093	15 286	12
			X				24 888	6 527	19 025	12
X				X			86 923	1 558	39 931	16
X					X		91 923	1 450	36 878	17
X						X	96 923	1 336	33 931	17

Table 3 Results of the economic analysis regarding the refurbishment of lighting systems

PV [kW_p]	**Lighting plant refurbishment**		**Initial investment**	**Annual en. expence**	**NPV**	**Pay-back time**
Peak (48.2)	Total	Partial	[€]	[€]	[€]	[yy]
X			81 923	1 690	42 550	15
X	X		96 820	1 261	38 921	16
X		X	84 371	1 250	55 533	13

4. Conclusions

In this work, a physiotherapy centre has been considered as case study and different design alternatives were studied to reduce the building power demand by means of on-site PV generation and refurbishment of the lighting system. A characteristic consumption profile has been developed using both the annual cumulative energy consumption data and short-term hourly monitoring data. The characteristic profile has been used as reference for the design of different alternatives of PV system, able to satisfy different amounts of the annual electrical energy demand, to store energy, and to sell overproduction to the electrical network. The case with highest installed capacity, which is the one with the best economic performance, has been coupled with a total and partial refurbishment of the lighting system, including new luminaires configuration with LED lamps, opaque film applied to windows instead of blind shadings and dimming and occupancy control systems. As regard to the PV system, we have found that by diminishing the installed power capacity, both net present values and payback time decrease. The installation of electrical storage systems is not convenient for the case study since the variation of the net presence value is small but the payback time increases remarkably. The combined PV system installation and intervention on the lighting system is not always the best choice. Indeed, when the lighting plant refurbishment solutions are applied to the whole building, lighting retrofitting is less attractive than just installing a PV system. If the refurbishment is focused on the most critical areas of the building, such as the therapy zone in the current case study, a more convenient solution can be found. Thus, with respect to the PV system alone, net present value has increased by about 30 % and payback time reduced by 2 years.

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