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Feasibility Study for the Installation of On-Site Energy Resources in a Public Building

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Abstract

Buildings contribute significantly to the total energy demand and account in some countries for up to 50 % of the primary energy consumption. The possibilities of local energy generation and affordable storage technologies led to an increased research on energy consumption in the building sector. In recent years, many national authorities adopted regulations to promote sustainable construction and energy efficiency in buildings. This paper presents a feasibility study for the installation of local generation systems in a public research center. A building energy assessment tool is employed to generate realistic demand profiles and to analyze the impact of changes in the building configuration on energy savings and economic benefits. The possible installation of a photovoltaic system and a cogeneration plant is examined with respect to possible cost savings due to a reduced external energy supply. The Net Present Value is used to evaluate the long-term viability of the installation of local energy generation systems considering different values for the annual increase in electricity prices. The procedure is suitable to identify critical building parameters with a strong influence on building energy demand and to study the economic feasibility of additional on-site generation systems.

Keywords – energy efficiency, demand forecast, sensitivity analysis, cost optimality

1. Introduction

Socio-economic development and technological progress give rise to a continuously increasing energy demand. In modern societies buildings significantly contribute to the energy demand and account in some countries for up to 50% of primary energy consumption [1, 2, 3]. In the last few years the scientific community and industrial sector intensified research on energy consumption and energy efficiency in the building sector. The growing interest is a result of many factors, including integration of renewable energy sources and storage systems, limitations of the infrastructure for energy production and transport as well as the opportunity to open up new business segments. More detailed knowledge about the demand patterns introduced by smart meters and the availability of affordable and reliable energy storage technologies foster the use of distributed and decentralized energy production. On-site generation in combination with local energy management is considered a feasible and inexpensive approach to reduce the impact of load variations and intermittent generation [4, 5, 6].

In recent years many national administrations introduced regulations and standards with the aim of reducing building energy consumption and promoting sustainable construction. However, the low construction rate in many developed countries – partly a consequence of the economic downturn and the financial crisis – almost cancels the effect of the implemented legal framework. Efforts made to improve energy efficiency should include the refurbishment of existing buildings, especially public buildings that commonly exhibit a large and inefficient energy use. Therefore, the prediction of the future building energy consumption, a key element in economic feasibility studies, attracts considerable interest both by industry and public research [7].

A large number of scientific publications deal with energy efficiency in public buildings, sustainable refurbishment and the use of on-site generation technologies. In [8] the realization of energy retrofit interventions for a sample of 37 public buildings was analyzed taking into account energy and cost effectiveness. The results of the study underline the importance of an economic analysis of the possible actions (e.g. interventions on the building envelope or installation of photovoltaic systems) to reach the required efficiency. A detailed review of 18 building energy retrofit analysis toolkits based on empirical methods, normative calculations and physics-based energy modeling is presented in [9]. The considered toolkits provide energy and cost savings solutions for commercial buildings, but present drawbacks such as emerging technologies not taken into account, limitations to certain building types or geographical regions or the problematic trade-off between level of detail, model precision and analysis time. The research and application of quantitative energy performance assessment methods for existing buildings is summarized in [10]. The authors underline that simulation tools might be the most powerful methods by providing detailed outputs. In contrast, the required inputs such as building parameters are frequently difficult to obtain or unavailable. A multi-objective optimization model for life-cycle cost analysis and retrofitting planning of buildings is proposed in [11]. The method allows finding the most cost-effective long-term solution for the retrofitting problem by maximizing the energy savings and economic benefits. A sensitivity analysis, i.e. the evaluation of the impact of small changes in building parameters on the energy demand, is employed to select the optimal retrofitting measures for Swedish residential buildings [12]. Similarly, the effects of changes in the energy prices and discount rates have been analyzed in [13] in order to design cost-optimal energy efficiency measures for a historic building.

1.1 Research Aim

The objective is the development of a procedure to study the economic feasibility of on-site energy generation systems in public buildings. Realistic demand profiles, generated by a modified version of a building energy assessment tool [14], are employed to analyze the effect of building modifications on energy savings and economic benefits. The integration of a sensitivity analysis can be used to identify critical building parameters and to design appropriate improvement measures. The procedure is useful in the evaluation of additional on-site energy generation devices and supports building managers in the decision-making process.

1.2 Overview

This paper presents a feasibility study for the installation of on-site energy resources in a public building. The used building energy assessment tool estimates the detailed energy demand for a given building configuration and the sensitivity analysis determines the elasticity of the energy consumption and costs with respect to modifications in the critical building parameters. The paper is organized as follows: Section 2 presents the employed methodology to calculate the building energy demand and to evaluate the effect of small changes in the building configuration. Section 3 describes a public building – a research center located in the area of Madrid (Spain) – and gives details on the used configuration. Results obtained in the feasibility study using a mathematical model of the considered public building are presented in Section 4. Finally, the most important conclusions are drawn in Section 5.

2. Methodology

Detailed demand profiles of a building are required to determine the economic feasibility for the installation of on-site energy generation systems. A modified building energy assessment tool – previously developed in [14] – is employed to estimate the energy consumption and supply costs of the building. The integrated sensitivity analysis allows examining the effect of changes in the building configuration.

The estimation of the energy consumption and the sensitivity analysis have been implemented in the Matlab environment. Matlab is a powerful mathematical program suitable for rapid development of algorithms and procedures that provides easy handling of large matrices and data structures as the ones used by the proposed tool.

2.1 Estimation of energy demand and supply costs

The estimation of the building energy consumption and the costs associated to the external energy supply is carried out in several steps (see Fig. 1). The tool employs the building configuration to estimate the energy demand for a complete year on an hourly basis. The estimated demand is then divided in its heating, cooling, electricity and domestic hot water (DHW) components. Afterwards, the demands are distributed on the considered on-site generation technologies (e.g. heat pump, chiller, etc.) and corresponding energy sources (e.g. electricity, gas, etc.). Finally, the total costs for the energy supply are calculated on basis of the demands covered by the energy sources.

The building model used in the estimation procedure considers both building properties and people related aspects. The flexible configuration allows modelling a wide range of different building types such as malls, office buildings and hotels. The used mathematical model takes into account the architectural characteristics, building usage, location, on-site facilities, presence of people and economic data.

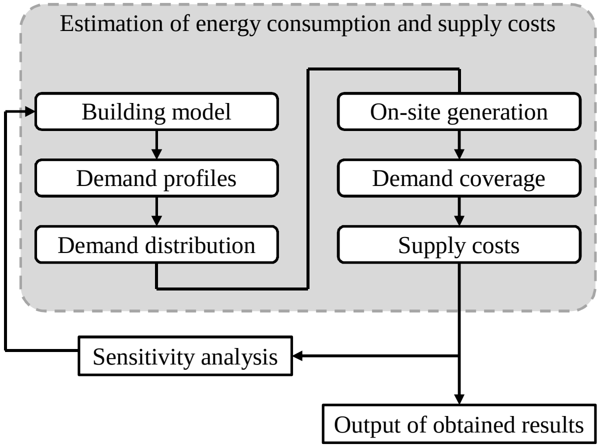

Fig. 1. General structure of the building energy assessment tool.

The demand profiles are estimated with the building model for an equilibrated energy balance, i.e. a static approach assuming a steady-state condition of the building is employed. The estimation procedure considers heat transfers between building and environment, energy demands for workplace conditioning (i.e. ventilation and illumination), energy consumption directly related to the presence of people in the building, other energy demands by equipment not included in other groups and non-dispatchable generation (e.g. solar collectors).

The estimated demands are divided in the following step in four independent components: heating, cooling, electricity and domestic hot water. The thermal demands are then distributed on the heating and cooling devices available in the studied building. Based on the distribution in the previous step, the energy demand of the on-site generation systems is computed. The necessary external energy supply corresponds to the sum of direct electricity demand and energy consumption of the installed generation devices. The annual energy costs for the building are then calculated applying the local energy tariffs. The detailed results – including the demand profiles, the demands due to heating and cooling, the use of on-site generation systems, the external energy supply and the costs are saved in spreadsheets and can be used for further data analysis or visualization purposes.

2.2 Sensitivity analysis of energy consumption and costs

The sensitivity analysis integrated in the tool determines the effect of variations in the building configuration on the energy consumption and supply costs (see Fig 1). The results allow identifying critical building parameters which can be then used to reduce consumption/costs and improve energy efficiency. The elasticity of variable Y (e.g. heat transfer by transmission or total energy costs) to changes in the parameter X (e.g. thermal transmittance of walls or energy prices) is defined as:

$$E_X^Y = \frac{\Delta Y}{Y} \frac{X}{\Delta Y} \tag{1}$$

The use of the elasticity concept allows an easy comparison of results without the need of additional data normalization. The sensitivity analysis compares the energy consumption and costs obtained with a modified building configuration with the results of the base case, i.e. the original parameters.

2.3 Profitability of investment

The feasibility study employs the Net Present Value (NPV) to evaluate the profitability of an investment in on-site generation technologies. Generally, the NPV is the sum of present values of cash inflows and outflows defined by:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{2}$$

In (2), the variable C_0 denotes the initial investment and C_t represents the cash inflow in the t-th period. The parameter r describes the discount rate and T is the number of time periods considered in the investment. A positive Net Present Value indicates a profitable investment, i.e. the expected benefits exceed the necessary capital expenditure.

3. Case study

The building considered in the case study is a public research centre (IMDEA Energy) located in the area of Madrid (Spain), see Fig. 2. With three storeys above ground level and one below, the building has a total gross floor area of 7900 m^2 and a capacity for up to 150 researchers. A large atrium – covered by a skylight – provides natural light and facilitates natural ventilation. The building was designed taking into account energy related issues such as thermal demand and energy efficiency. After the completion of the building in 2012, IMDEA Energy achieved the maximum energy rating (class A) and has been certified as a sustainable building (LEED Gold).

Fig. 2. View on the building considered in the case study.

The building is equipped with an 80 mm back-ventilated insulation to mitigate the effect of extreme temperatures (35 ºC and above) during summer. Different external claddings have been used to cover the building façade: lacquered panels for the research module, quartzite for the auditorium and corrugated panels for the pilot laboratories. Depending on the orientation of the glass façade, different solutions have been chosen to reduce the incidence of light and thermal radiation. Fixed parasols have been installed on the south and east sides whereas automatically controllable sunshades are used on the west side of the building. The heat transfer coefficient (U-value) and solar energy transmittance (g-value) of the different materials used to cover the building façade are given in Tab. 1.

Table 1. Heat transfer coefficient and solar energy transmittance of the building envelope.

Type/material	U-value ($W/m^2/K$)	g-value (%)
Stone	0.392	-
Panels	0.436	-
Roof	0.353	-
Glass façade	1.90	41
Windows	2.29	72
Skylight	1.30	28

The building has been equipped with different technologies for heating, cooling, production of domestic hot water, electricity generation and storage. The main systems include: ground-coupled heat pump (GCHP), air-source heat pump (ASHP), combined heat and power (CHP), air handling unit (AHU), fan coil unit (FCU), solar photovoltaic system (PV), solar thermal system (STS), electric water heater (EWH), uninterruptible power supply (UPS), emergency power system and capacitor bank for reactive power compensation. All devices are supervised and controlled in real time through the integrated building management system (Honeywell Enterprise Buildings Integrator).

Throughout the rest of the document a simplified building configuration will be used (see Fig. 3). In the considered setup, the solar thermal system and the electric water heater provide the required domestic hot water. The ground-coupled and air-source heat pumps are used both for space heating and cooling. Finally, the electricity demand is covered by the main grid (low voltage connection).

4. Results

The building energy assessment tool has been used to study the economic impact of installing PV and CHP in the considered building. Before the feasibility study, the basic building configuration (see Section 3) was used to determine the annual energy demand of 898 kW and supply costs of 156000 € (see Tab. 3 for the exact values). The costs were calculated with the common Spanish time-of-use-tariff 6.1A (1 kV to 30 kV).

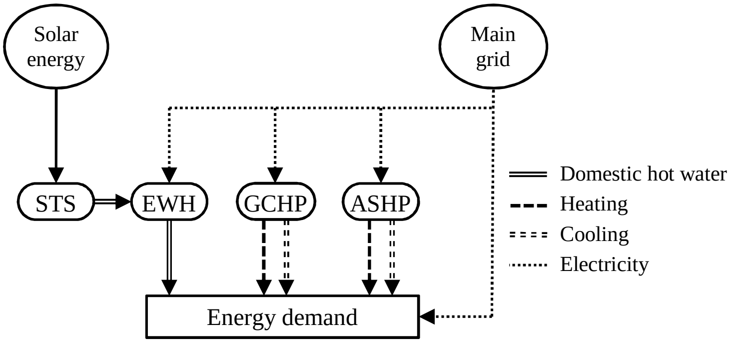

Fig. 3. Simplified configuration of the building considered in the case study.

The sensitivity analysis was carried out to check the effect of different changes in the building configuration (some of the results are given in Tab. 2). It can be observed that small changes in the permitted building temperatures and the energy tariff have a considerable effect on the total energy costs. In contrast, some modifications on the building envelope (e.g. transmittance and solar factor) do not affect the overall energy costs.

Table 2. Results obtained in the sensitivity analysis for changes in the building configuration.

Building parameter	Change in parameter	C_{total}
Minimum temperature	-1 ºC	- 0.50%
Maximum temperature	+1 ºC	- 0.52%
Electricity tariff: power charge	-1%	- 0.27%
Electricity tariff: energy charge	-1%	- 0.73%
External walls: transmittance	-1%	0.00%
Windows and skylight: transmittance	-1%	0.00%
Windows and skylight: solar factor	-1%	0.00%

The building energy assessment tool was then used to evaluate the effect of additional generation systems without considering the initial investment. The installation of PV and CHP systems with nominal powers of 35 kW and 110 kW were considered in the study. For both systems, the simulations were carried out with and without tax on self-consumption. The values for the tax were taken from a Spanish draft law [15] with a power charge between 4.93 €/kW and 22.65 €/kW and an energy charge between 0.71 c€/kWh and 1.93 c€/kWh, depending on the time of use. The possibility to sell energy to the main grid (reward of 4 c€/kWh at any hour) was considered in the third simulation with the PV system. The results given in Tab. 3 compare the different cases with the original building configuration. In the case of the tax on self-consumption, both systems lead to an important increase in energy costs (+15.63 % and +14.84 %). In contrast, self-consumption without the tax results in some cost reduction (-2.31 % and 3.10 %). Only a very small cost saving is achieved from the combination of PV system and grid export (-1.13 %). It is clear that the considered tax jeopardizes any advantage of local generation systems.

Table 3. Results of PV and CHP systems with and without tax on self-consumption.

Case	Q_{gas} (kWh)	Q_{grid} (kWh)	C_{total} (€)	*Diff.* (%)
Original building configuration	-	898.3	155,970	-----
PV: self-consumption, with tax	-	865.9	180,349	+15.63
CHP: self-consumption, with tax	236.8	779.5	179,122	+14.84
PV: self-consumption, w/o tax	-	865.9	152,369	-2.31
CHP: self-consumption, w/o tax	236.8	779.5	151,142	-3.10
PV: grid export, w/o tax	-	898.3	154,201	-1.13

Finally, the economic feasibility of different PV installations (40 kW, 60 kW and 80 kW) considering the initial investments was studied. The analysis was carried out for a service life of 20 years and different annual increments of the electricity prices. The net present values (NPV) in Fig. 4 show that the considered PV installations without tax on self-consumption start being profitable for annual increases in the electricity price between 2.15 % and 2.4 %. In the case of the tax on self-consumption, profitability of the PV systems starts for annual electricity price increases between 3.15 % and 3.4 %. The results underline that the feasibility of the PV installations depends heavily on the development of the electricity prices.

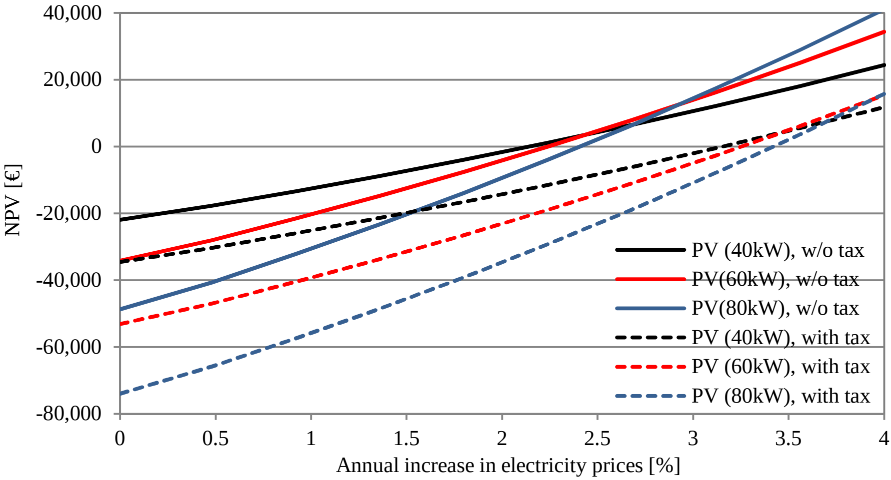

Fig. 4. Net Present Values of PV systems (with and without tax on self-consumption) over the entire service life for different annual increases in electricity prices.

Conclusions

This paper presents a feasibility study for the installation of on-site energy generation systems in public buildings. A building energy assessment tool is employed to generate realistic demand profiles for an entire year and to estimate the associated supply costs. The used tool takes into account environmental interactions, workplace conditioning, personnel consumption, on-site dispatchable and non-dispatchable generation as well as other energy demands. The integrated sensitivity analysis allows identifying critical parameters that can be used to reduce energy consumption and to achieve cost savings. The cost-effectiveness of additional on-site generation systems is determined using the concept of Net Present Values. Including the initial investment and possible cost savings over the service life of the installation, the study provides building managers with helpful information in the decision making process.

The proposed procedure is used in a case study – a public research centre located in the area of Madrid (Spain) – to evaluate the installation of PV and CHP systems. The results showed that the introduction of a tax on self-consumption has a strong influence on the profitability of local generation. Both systems gained a small benefit without the tax. In contrast, the application of the tax led to considerable economic losses. The Net Present Values are used to check the economic feasibility of different PV installations over the entire service life. The results showed that the PV systems without tax on self-consumption become profitable for annual electricity price increases between 2.15 % and 2.4 %. In the case of the tax, profitability is reached for annual increases in the electricity prices between 3.15 % and 3.4 %.

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