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Economic and environmental analysis of energy renovation packages for European office buildings

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ABSTRACT

A large share of the buildings in Europe are old and in need of renovation, both in terms of functional repairs and energy efficiency. While many studies have addressed energy renovation of buildings, they rarely combine economic and environmental life cycle analyses, particularly for office buildings. The present paper investigates the economic feasibility and environmental impact of energy renovation packages for European office buildings. The renovation packages, including windows, envelope insulation, heating, cooling and ventilation systems and solar photovoltaics (PV), were evaluated in terms of life cycle cost (LCC) and life cycle assessment (LCA) through dynamic simulation for different European climates. Compared to a purely functional renovation, the studied renovation packages resulted in up to 77% lower energy costs, 19% lower total annualized costs, 79% lower climate change impact, 89% lower non-renewable energy use, 66% lower particulate matter formation and 76% lower freshwater eutrophication impact over a period of 30 years. The lowest total costs and environmental impact, in all of the studied climates, were seen for the buildings with the lowest heating demand. Solar PV panels covering part of the electricity demand could further reduce the environmental impact and, at least in southern Europe, even reduce the total costs.

1. Introduction

Around 40% of the final energy use in Europe is accounted for by buildings [1]. In new buildings, the trend since 40 years has been towards better energy performance [2,3], and today it is possible to build houses that are more or less self-sufficient in energy. However, as more than 50% of the existing residential buildings and 40% of the office buildings in Europe were built before 1970 [2,3], renovation is an important measure for reducing the energy use of the building stock [4]. Beside the need to improve building envelopes, efficient energy generation and distribution systems are also vital in this context.

In terms of heated floor area, the residential building stock in the EU-27 is 15 times larger than the office building stock [2], and in previous studies on building renovation, the focus has predominantly been on residential buildings [5]. However, with nearly 1 billion m^2 heated floor area, office buildings are also important to consider. The average energy use in European office buildings, not including electrical appliances, is 232 kWh/(m^2 y), out of which 69% is used for heating, 9% for cooling, 4% for domestic hot water (DHW) preparation and 17% for lighting [2]. The favored energy carrier in non-residential buildings is electricity, although for heating gas and oil are also very common. District heating is mainly used in northern Europe, and coal accounts for around 10% of the primary energy use in non-residential buildings in Lithuania, Poland and Slovakia [2].

Common interests between EU member states have led to numerous research projects on energy efficient office buildings, including EU projects OFFICE [6], Cost-Effective [7] and iNSPiRe [8],

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Nomenclature

AWHP	Air-to-water heat pump
CO2	Carbon dioxide
DHW	Domestic hot water
EPS	Expanded polystyrene
FC	Fan coil
HVAC	Heating, ventilation and air conditioning
LCA	Life cycle (environmental) assessment
LCC	Life cycle cost
MVHR	Mechanical ventilation with heat recovery
NPV	Net present valueNet present value
PEF	Primary energy factor
PV	Photovoltaic
RC	Radiant ceiling
RPS	Reference period of study
U	Heat transfer coefficient for building parts, $W/(m^2 K)$
"25"	Building renovated to have a heating demand of $25 kWh/(m^2 y)$
"45"	Building renovated to have a heating demand of $45 kWh/(m^2 y)$
"REF"	Reference case; building renovated without reducing the heating demand

and IEA EBC projects Annex 35 [9] and Annex 46 [10]. Within the OFFICE project, Hestnes and Kofoed [11] investigated retrofitting strategies for offices on ten locations in Europe and found potential for substantial reduction of purchased energy. As part of the same project, Dascalki and Santamouris [12] assessed the energy saving potential of different renovation scenarios for five office building types in four European climatic regions. The scope of this investigation, however, was limited to economic aspects and to the 15 countries that were members of the EU before 2004. The Cost-Effective project focused on façade-integrated energy systems for high-rise non-residential buildings, including solar collectors, building integrated photovoltaics, ventilation with heat recovery and a solar thermal assisted heat pump [7]. The scope of the project ranged from technical development and business models to life cycle assessment (LCA). The iNSPiRe project aimed to develop deep energy renovation solutions for residential and office buildings, and to achieve a primary energy use after renovation of 50 $kWh/(m^2 y)$ for heating, cooling, ventilation, lighting and DHW [8]. The renovation packages were evaluated through simulation of so-called target buildings, which were based on statistics on construction, size and energy performance of buildings in the EU, and the simulations results were gathered in a publicly available database [13].

The LCA methodology was developed through the 1970s and 80s, and has been used for environmental impact assessment in the building industry since 1990 [14]. However, LCA studies on renovation of buildings are to present date scarce, especially studies that combine environmental and economic aspects [14,15], and the studies that have been done generally focus on residential buildings [16–18]. On the non-residential side, Ardente et al. [19] performed an LCA on six European public buildings and found insulation to be the most environmentally beneficial renovation measure, followed by new windows and energy efficient lighting. Liu et al. [20] showed that office space cooling with chilled ceiling panels is viable, from a life cycle perspective, in a tropical climate. In an integrated energy and environmental LCA of different building envelope scenarios for offices, Azari [21] found a low window-to-wall ratio and fiberglass insulation to be beneficial. Also, the operational phase was found to account for the largest environmental impact in almost all categories, which is concurrent with other studies [22,23].

The present study was conducted within the frame of the iNSPiRe project. The aim of the study was to assess the economic and environmental aspects of systemic renovation packages for typical European office buildings, including insulation, windows, energy generation and distributions systems and solar photovoltaics (PV), in three European climates. A total of 255 different renovation cases were simulated and analyzed in terms of life cycle cost (LCC), LCA and primary energy use. In addition to what can be found in the iNSPiRe database [13], this paper gives a direct comparison of different energy generation and distribution systems, presents the environmental impacts of different phases in the life cycle, assesses the sensitivity of certain economic parameters and compares energy renovation cases to renovation without energy efficiency measures.

2. Method

2.1. Building model and boundary conditions

The studied buildings and energy systems were modelled and simulated in TRNSYS 17 [24], while system sizing and post-processing calculations were done in Excel tools developed within iNSPiRe. A more detailed description of the modeling and simulation methodology is given in the iNSPiRe report D6.3a – Performance of the Studied Systemic Renovation Packages – Method [25].

Within the iNSPiRe project, the EU-27 member states were divided into climatic regions, based on the number of heating degree days [26], and target building models were created for each region. Heat transfer coefficients (U-values) of building parts were identified for different construction periods and weighted by the heated floor area of each country to give average U-values for the whole region [27]. The building models used in this study were defined as typical European office buildings from the period 1945–1970 in the Nordic, Continental and Mediterranean regions [2,3,28]. Climate data for Stockholm (Sweden), Stuttgart (Germany) and Rome (Italy), respectively, were used in simulations. The building model had six zones: two zones each (south side and north side) representing the ground floor, a middle floor and the top floor, respectively. No heat transfer or air exchange was considered between the zones. By multiplying inputs and outputs for the heating and cooling system of the middle floor by three or five, buildings with five or seven floors could also be simulated. In the present study, office buildings with five floors and a heated area of 1620 m^2 are treated. The building was oriented at a 45° angle from north-south, with the longest façades towards south-east/north-west, and had a glazing ratio of 30% on all façades. A layout of the building model is shown in Fig. 1.

Internal gains from people were assumed to be 120 W/person, corresponding to an activity level of seated, very light writing [29], with 0.11 $persons/m^2$. The office was assumed to be occupied Monday – Friday from 8:30 to 17:30, with exception for a one hour lunch break and two weeks of holidays, one week in August and one week at the end of December. Computers, monitors and other electronic equipment was assumed to be of modern, energy efficient type after renovation, contributing 7 W/m^2 during office hours, while internal gains from the new lighting amounted to 11.6 W/m^2. The ventilation was on during office hours, plus one hour before and after, with an air change rate of 40 l/h per person (1.48 h^{-1}). In addition, a constant infiltration rate of 0.07 h^{-1} was considered for the cases with mechanical ventilation with heat recovery (MVHR), and 0.15 h^{-1} for the cases with mechanical exhaust ventilation (see Table 1). The MVHR was considered to have a thermal efficiency of 85%, with bypass of the heat recovery unit when the average convective temperature in the office was higher than 23 °C or higher than the