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A dynamic energy performance-driven approach for assessment of buildings energy Renovation—Danish case studies

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ABSTRACT

In this study, four buildings in Aarhus, Denmark are considered for energy renovation analysis and assessment aiming to enhance their energy performance. A systematic and dynamic energy performance-driven methodology for buildings energy modelling, simulation and renovation was developed and implemented based on an overall technical, economic and environmental assessment. Detailed dynamic energy performance models were developed for the buildings considering various specifications, envelope characteristics and energy supply systems configurations. The models were calibrated using actual energy consumption data and occupancy schedules. Buildings primary energy consumption in the range of 158–192 kWh/m^2 of indoor heated area was reported, highlighting large potential for energy performance improvement. Based on field visits, systems and components inspections, technical managers interviews and users feedback, various energy renovation measures and packages were prioritized and investigated employing a holistic approach and considering the technical, economic and environmental impacts of each package. It was found that a renovation package comprising LED lights, efficient equipment, heating circulation pump replacement and ventilation system upgrade is favourable allowing average energy savings of 27.7% with a payback period less than 4 years and average CO_2 emissions reduction of 5.1 t/year in the four buildings. However, considering indoor air quality and thermal comfort along with the Danish building energy standards and requirements, a deep energy retrofit package was recommended through improving energy supply systems efficiency and upgrading the buildings envelope. Average energy savings of around 50% were reported with an estimated payback period of 11 years. Moreover, the option of including a 4 kWp PV system along with the deep energy retrofit package was investigated and was found to save up to 71% on the primary energy consumption with average reduction of 115 kWh/m^2, allowing the four buildings to be classified as BR15 Renovation Class 1, the highest class for renovated buildings in Denmark.

1. Introduction

Buildings in the US and EU contribute to about 40% of the overall energy consumption with a significant share of 36% on the CO_2 emissions [1,2]. Thus the building sector is considered as a priority by the EU when it comes to attaining the ambitious 2020 and 2050 energy and climate objectives and improving the energy security, throughout enhancing the building stock energy efficiency, allowing huge reductions on the overall energy consumption and the corresponding greenhouse gas emissions [3–5]. Although the majority of the building regulations and standards are targeting new and future buildings, existing buildings still constitute the largest share in the buildings stock and shall be targeted in the holistic energy efficiency improvement actions and legislations throughout systematic and well-organized renovation and retrofit processes taking into account specific buildings characteristics and specifications along with different economic, technical and functional constraints [6–8]. Building energy renovation could be defined as a holistic process of improving the energy performance and the thermal indoor quality of existing buildings throughout implementing energy efficient and cost-effective measures and techniques targeting various building components including different energy production and supply systems, building envelope and constructions, building management and control strategies and renewable and alternative energy units [9–13]. Currently, the majority of buildings energy renovation and retrofit processes are driven by the need to change and not the choice to improve the energy performance and enhance the indoor thermal comfort

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Nomenclature

BCL	Building component library
BR	Building regulation
EPBD	Energy performance of building directive
HVAC	Heating, ventilation, and air conditioning
LED	Light-emitting diode
PAT	Parametric analysis tool
PV	Photovoltaic
SPP	Simple payback period

with no considerations for energy systems efficiency and operation and building constructions and materials lifetime in the decision-making process [14]. To save time and resources, when renovation is decided to be carried out for a specific building, the process shall include an overall implementation of energy efficient measures and components upgrade as needed taking into account the building age, systems functionality and envelope constructions. Moreover, energy renovation shall aim to improve the existing building performance to a level comparable to modern and newly built buildings, based on the up-to-date building standards and energy labelling legislations, employing an overall methodical and organized screening for various renovation solutions and efficient measures. Following this screening process, an energy renovation package is selected considering a trade-off between energy savings, investment and operation costs and emissions reductions [15]. Building energy renovation has been a very hot topic in the last three decades with a substantial body of literature highlighting the potential of existing buildings energy renovation and examining various theoretical methodologies and practical applications from the technical, economic, environmental and legal perspectives [16–20]. Energy renovation scenarios were considered and investigated in eight EU countries, Spain, Portugal, Switzerland, Italy, Austria, Sweden, Norway and Denmark aiming to assess the trade-offs and balances between using renewable energy systems and employing energy efficient measures and technologies [21]. Business models for single family and domestic buildings in Nordic countries were presented by Mahapatra et al. [22] employing a full-service package starting with consulting and auditing, then actual renovation work design and quality control, ending with commissioning and financing. In addition, the potential of buildings energy renovation was investigated and presented from different perspectives considering case studies in various countries, including Italy [23], Sweden [24], Belgium [25], Netherlands [26] and China [27], highlighting the importance of energy resources price, investment costs and financial energy policies in any energy renovation process.

Nevertheless, the impacts of each building energy renovation process shall be assessed and quantified in the planning and decision-making phase [28–30]. Various approaches and methodologies were developed and implemented to aid energy renovation decision-making and to select the optimal renovation measures combination. In their study, Rysanek et al. [31] suggested that the computational efficiency of large-scale retrofit processes analysis could be enhanced through decomposing holistic black box models into various discrete components and hence estimating the energy performance using sequential models. In addition, they proposed a multidisciplinary model, combining these sequential models with an economic cost-benefit model, and suggested that using non-probabilistic optimization and decision rules is a useful approach for scenario modelling in the case of building energy retrofits. They recommended that detailed dynamic building energy performance simulations are indispensable to quantify the impact of various retrofit measures and decisions in complex renovation processes. In their study, Yang et al. [32] investigated domestic buildings energy retrofit in Tianjin, China from an architectural perspective. A working procedure was presented with three major stages, building performance diagnosis, retrofit proposal and prediction and feedback. Three case study buildings, which were built in 1981, 1995 and 2002, were selected to implement the retrofit working procedure. It was found that energy retrofit for the three buildings would lead energy savings in the range of 36–78% with corresponding CO_2 emission savings between 44% and 92%, where the savings are inversely proportional to the building age. Eliopoulou et al. [33] have investigated building energy renovation from another perspective, presenting a new deep energy retrofit strategy, called Architectural Energy Retrofit, aiming to link the building energy demands with the architectural concept's bioclimatic potential. Under the proposed strategy, various renovation measures were evaluated from the technical and architectural perspectives, aiming to prioritize fixing, restoring, modifying or updating architectural elements and structures to minimize building's energy demands as well as attaining the revival of the microclimatic conditions and the non-technical impacts of the well-designed space. A school was examined as a case study to test the strategy, and 44% reduction in the energy consumption was reported by architectural interventions only without any modifications in the technical systems specifications. However, the suggested strategy raises major concerns as it requires the architect to have full knowledge of the energy design and management techniques and have large responsibilities to implement these at the design stage. In addition, no standardized results are documented regarding the positive impacts of implementing such architectural-based renovation strategy in improving the energy performance which hinders the confidence in such approaches. A differential evolution algorithm was employed by Wang et al. [34] as a basis for a multi-objective optimization model for life-cycle cost analysis and buildings energy retrofit processes planning. A net present value-based economic analysis considering life-cycle cost was implemented in the formulation of the objective functions. The approach aims to maximize energy savings and economic benefits by assessing multiple combinations of alternative retrofit measures. Jafari et al. [35] proposed a decision-making framework for building energy retrofits that aims to calculate economic benefits of energy retrofitting in terms of reduction in the life cycle cost, determine the optimal retrofit budget and select the optimal retrofit strategy to enhance the economic impacts. A simplified energy performance prediction method is employed, combining static and dynamic modelling approaches. A case study of a 150m^2 house from the 1960's in Albuquerque, New Mexico is considered and a budget of $11,000 for energy renovation was reported, implementing measures including programmable thermostat, efficient lights, walls and roof insulation, and solar thermal units. In a previous study [36], the authors showed that employing dynamic energy performance models are instrumental in assessing the technical impacts of implementing various energy measures and packages in deep energy retrofit processes of office buildings in Denmark. A 2500 m^2 office building in Denmark was considered as a case study and respective savings of 51.3% and 36.6% on heating and electricity consumption were reported employing a systematic and dynamic energy renovation approach to select the optimal retrofit package.

The current study aims to establish a systematic methodology for Danish buildings energy modelling, simulation and energy renovation assessment based on technical, economic and environmental perspectives employing detailed dynamic energy performance models that take into account building envelope characteristics and energy supply systems configuration. Unlike the dynamic and multi-objective energy renovation approaches and methodologies presented above, and the systematic renovation