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DEEP ENERGY RETROFIT VS IMPROVING BUILDING INTELLIGENCE – DANISH CASE STUDY

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ABSTRACT

This study provides a preliminary assessment of the trade-off between deep energy retrofit and improving the building intelligence within an energy renovation process. A standard Danish office building from the 1980's is considered as a case study. A detailed energy model was developed in EnergyPlus to simulate the dynamic performance of the case study building. Various deep energy retrofit measures were implemented and assessed. In addition, different measures to improve the energy efficiency and intelligence of the building were investigated and simulated with emphasis on European Standard EN 15232 recommendations for control and management of heating, ventilation and lighting systems.

INTRODUCTION

The building sector was prioritized by the EU aiming to achieve the 2020 and 2050 energy and environmental objectives through enhancing the building stock performance and reducing energy consumption and the corresponding emissions. In this context, the Energy Performance of Building Directives (EPBD) in 2002 and 2010 (EPBD 2002, 2010) have set strict guidelines and clear commitment to improve buildings' energy performance, with an estimated potential of 30% in terms of energy savings in EU buildings by 2020. The EPBD requires the EU member countries to develop energy-efficient and cost-effective regulations and standards for newly built buildings and establish minimum acceptable performance standards for existing buildings. Moreover, the Energy Efficiency Directive in 2012 (EED 2012) has urged EU countries to develop comprehensive long-term national plans for public buildings energy renovation with an annual renovation of governmental buildings at 3% rate. Building energy renovation is defined as the overall process to improve the energy performance and enhance the thermal comfort and indoor air quality through implementing highly efficient and cost-effective energy measures and techniques (Nielsen et al. 2016). However, the current approach in the majority of energy renovation projects and applications is driven by the need to change and modify with the absence of a proper decision-making strategy considering different components including building envelope and energy systems integration (Friege and Chappin 2014). One of the major energy renovation approaches which has gained vast interest in the recent years is the 'Deep Energy Retrofit' (DER) (Jradi et al. 2017), which is an overall whole-building renovation approach to attain significant energy savings. The Massachusetts Save Energy Retrofit Builder Guide defines DER as the retrofit of the building enclosure and systems resulting into a high performance building (BSC 2013). The IEA-EBC Annex 61 defines DER as a major renovation project resulting into at least 50% energy savings with an associated improvement in the thermal comfort and indoor air quality (Annex 61 2012)..

In addition to the positive impacts of such deep energy retrofit projects in terms of saving energy, reducing emissions and improving thermal comfort and indoor air quality, this holistic renovation approach results in lowering life cycle costs including operational and maintenance costs in addition to reducing investment costs as all renovation measures are implemented in one phase instead of several consecutive phases. Under the IEA ECB Annex 61, Mørck et al. (2016) reviewed and analyzed information on 26 deep energy retrofit case studies in Austria, Denmark, Estonia, Germany, Ireland, Latvia, Montenegro, Netherlands, UK and US. They reported the different energy renovation measures and techniques implemented as shown in Table. 1. It is found that the majority of the deep energy renovation packages target insulation of the envelope components, lighting, ventilation systems upgrade and supply and distribution systems improvement. On the other hand, as every building is different in terms of location, geometry, type, use, envelope, energy systems and occupancy behavior, implementing a deep energy retrofit approach through upgrading the energy systems and enhancing the building envelope may not be the optimal solution for every building case. Therefore, establishing a balanced trade-off between deep energy retrofit measures and improving the building intelligence is a wise and effective solution to achieve the maximum energy savings desired.

Table 1 Deep energy retrofit measures implemented

Renovation Measure (Number of Case Studies Implemented)	**Measure Category**
Wall insulation (23) Roof insulation (22) Floor insulation (15) New windows/doors (23) External shading/ daylight strategy (9) Roof lights (6)	Building Envelope
Efficient lights/ light control (22) BEMS (3)	Lighting/ Electrical
Mechanical ventilation with heat recovery (18) New ventilation systems (13) New heating/cooling distribution system (17) New heat supply radiators/floor heating (5) Air-source heat pumps (5)	HVAC
Ground couple heat pump (7) Solar thermal systems (10) Photovoltaic panels (10)	Renewable Energy Systems

The notion of 'Intelligent Buildings' dates back to the 80's and different definitions of Intelligence in buildings were provided in addition to highlighting various associated intelligence key indicators. One of the earliest definitions for intelligent buildings was provided by the Intelligent Building Institution in the US (Ghaffarianhoseini et al. 2012), being the building which "integrates various systems to effectively manage resources in a coordinated mode" aiming to improve the performance, enhance flexibility and reduce investment and operating costs. In addition, Leifer et al. (1988) defined an intelligent building as the one employing an information communication network where two or more energy systems are controlled automatically, guided by predictions based on the knowledge of the building and its use. In overall, intelligent buildings improve energy performance efficiency and flexibility as well as maintaining proper thermal comfort and indoor conditions by integrating various energy technologies, building systems, and control and automation strategies. Additional studies stated that building intelligence is not only associated with controlling and managing the energy systems, but also with the capability to respond continuously to the user expectations and the changing demands of the occupants and the environment (Wigginton and Harris 2002). Ochoa and Capeluto (2008) stated that integrating intelligent building control and management strategies with passive design and envelope improvements allows improving the sustainability level of the building performance. Volkov et al. (2015) reported that machine learning algorithms are not useful in evaluating building intelligence due to the probabilistic nature, and presented a tool to simulate building operation and evaluate the intelligent quotient employing a dynamic building model. A comprehensive review was provided by Ghaffarianhoseini et al. (2012) regarding definitions, performance indicators, benefits and challenges of intelligent buildings from an international perspective. They reported that one of the major components characterizing an intelligent building is the level of smartness and technology awareness. In this context, building intelligence in this study is characterized by the level of building energy systems automation and control with the European standard EN 15232 on impact of Building Automation, Controls, and Building Management (EN15232 2007), being the baseline reference.

Considering the technical and economic positive impacts of deep energy retrofit in existing buildings and the added-value provided by improving building intelligence using automation and control strategies, this paper examines the trade-off between deep energy retrofit and improving the building intelligence within an energy renovation process. A standard office building in Denmark from the 1980's is considered as a case study, and a holistic energy model is developed in EnergyPlus to simulate the building dynamic energy performance. Different deep energy retrofit measures and techniques are implemented and assessed in addition to various measures to improve the energy efficiency and intelligence of the building with emphasis on European Standard EN 15232 recommendations. The technical impacts of the deep energy retrofit and improving building intelligence measures are reported and analyzed to assess various approaches and investigate a proper balance of measures to improve the building performance.

CASE STUDY

A typical office building from the 1980's in Denmark is considered to investigate the technical impact of various deep energy retrofit measures and techniques in addition to measures targeting improving building intelligence using automation and control strategies on the level of different energy supply systems. Denmark has set an ambitious holistic energy goal to become a fossil-free country by 2050 (Lund and Mathiesen 2009), and rely solely on renewable energy resources to fulfil various energy demands with the aim to reduce emissions by more than 80%. When it comes to the building sector, Denmark is not an exception where the building stock consumes around 35-40% of the whole country energy consumption and the Danish government has prioritized this sector aiming to improve the energy performance of newly built buildings with strict technical and environmental standards. Nevertheless, considering that existing buildings which were built before 1979 comprise more than 75% of the building stock in Denmark, the government has highlighted the potential of carrying out a holistic energy renovation process on the whole country level. In this context, a comprehensive strategy for energy renovation was developed, "Strategy for the energy renovation of the existing building stock" (Strategy for Energy Renovation of Buildings 2014), with 21 initiatives to aid energy efficient and cost-effective renovation projects. The considered case study building complies with the BR77/82 Danish building regulation in terms of envelope and energy consumption. With no building automation and control system, the building is labelled as Class 'D' based on the European Standard EN 15232 "Energy performance of buildings – Impact of Building Automation, Controls and Building Management". In terms of energy supply systems, the office building is assumed to be connected to a district heating loop and served by an uncontrolled heating system using radiators. In addition, the office building employs an uncontrolled mechanical ventilation system with a conventional uncontrolled lighting system in various rooms. A 3D model of the 800 m^2 office building is developed in Sketchup Pro as presented in Figure 1. In addition, the major envelope components' overall heat transfer coefficient is shown in Table 2, considering that the building is complying with the Building Regulation BR77/82. The building overall window to wall ratio is around 34% and an occupancy intensity of 0.1 person/m^2 is assumed with a standard Danish office building occupancy schedule.

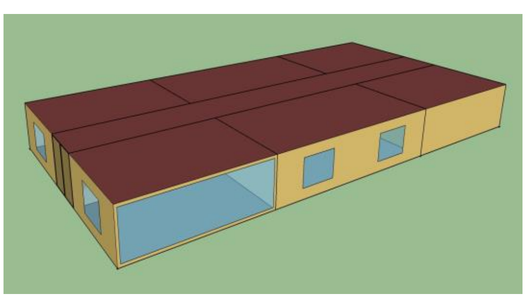

Figure 1 Office building 3D model

Table 2 Major envelope components U-value

Building Component	U-Value Case Study ($W/m^2.K$)	U-Value BR77/82 ($W/m^2.K$)
Exterior Wall	0.38	0.4
Roof	0.19	0.2
Floor	0.27	0.3
Windows	2.8	2.9

BUILDING MODELING AND SIMULATION

A detailed holistic energy model is needed to simulate the dynamic energy performance of the considered office building in its current state in addition to simulating the impact of various energy renovation measures to be implemented. The holistic building model takes into account various building specifications and characteristics including location, geometry, climatic conditions, envelope constructions and materials, HVAC systems and occupancy behavior. The overall methodology of the working process is presented in Figure 2. EnergyPlus is employed as a basis for building modeling and simulation, offering a free and well-established and validated modeling and simulation engine, with the flexibility to communicate with different aiding tools. In this work, EnergyPlus is supported by two tools: Sketchup Pro to draw the building overall 3D model and provide a detailed representation for the building geometry and physical envelope; in addition to OpenStudio as a user-friendly modeling interface to model various building components and systems along with schedules, loads and operation modes. The holistic building modeling and simulation methodology is described in details by Jradi et al. (2018). This methodology was adopted for the considered case study office building where a 3D model was drawn in Sketchup Pro and used as an input to OpenStudio where the overall energy model was developed with different building specifications.

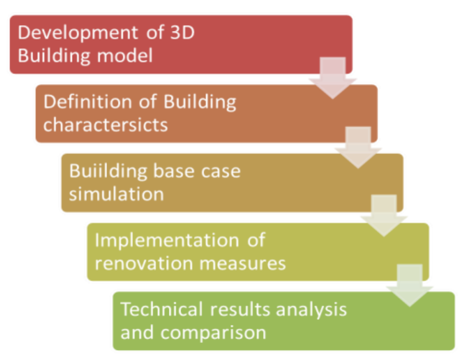

Figure 2 Overall working methodology

Following the development of the energy model, the EnergyPlus simulation engine is employed to simulate the overall dynamic energy performance of the office building throughout the year. Based on the annual dynamic energy simulation conducted, it was found that the office building consumes around 82.5 MWh for heating and 76.7 MWh for electricity. Considering that we are mostly interested in the holistic performance of the building, rather than the hour-to-hour operation, Figure 3 depicts a breakdown of the overall annual energy consumption of the considered office building case study. It is shown that around 52% of the energy consumption is used for heating where lighting, equipment and ventilation have a share of 15%, 23% and 8% respectively. In addition, Figure 4 presents the monthly heating energy profile along with the average monthly ambient air temperature. It is shown that the heating needs from June to August are minimal where the major heating season extends from November until March with a monthly demand exceeding 10 MWh.

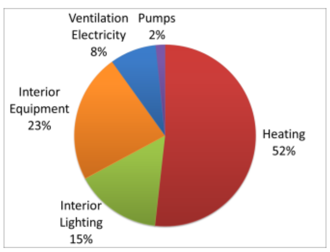

Figure 3 Office building energy consumption breakdown

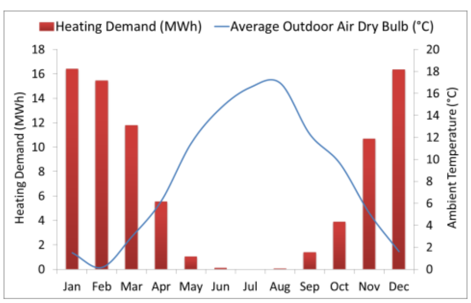

Figure 4 Monthly heating demand profile

Table 3 presents the office building primary energy consumption, calculated considering the BR15 (BR15 2015) current building regulation which sets high standards in terms of energy consumption and building envelope and components. The annual primary energy demand numbers included in the table accounts for the total building consumption for heating, ventilation, cooling and lighting in kWh/m^2 heated floor area, excluding energy consumed by interior equipment. A weighting factor of 1 is used for heating and 2.5 for electricity. The primary energy consumption of the building in its current state was found to be around 228.6 kWh/m^2. As shown in the table, if this building is going to be renovated and comply with the BR15 building energy standard, it shall consume less than 139 kWh/m^2 to comply with Renovation Class 2 and less than 73.36 kWh/m^2 to comply with the more strict Renovation Class 1. In addition, if a similar new office building with the same interior area is to be built today, such building shall have a maximum annual primary energy consumption of only 42.25 kWh/m^2. The numbers presented in the table demonstrate the large potential of energy renovation and performance improvement of such a typical 1980's office building in Denmark, with the need to reduce the primary energy consumption by at least 39% to comply with the minimum acceptable building standard for renovated existing buildings. In terms of the building envelope, Table 4 shows that the current envelope major components U-value need a major upgrade to comply with the envelope specifications set by BR15 standard. Considering the simulation results and the comparison with the building regulation BR15, the next section will investigate the impact of implementing various deep energy retrofit and intelligence improvement measures on the holistic office building performance.

Table 3 Building primary energy consumption vs BR15 standards

	Primary Energy Consumption (kWh/m^2)
Office Building current state	228.6
BR15 Renovation Class 2	139
BR15 Renovation Class 1	73.36
BR15 for similar new building	42.25

Table 4 Building envelope components vs BR15 standards

Building Component	**U-Value Case Study (W/m^2.K)**	**U-Value BR15 (W/m^2.K)**
Exterior Wall	0.38	0.18
Roof	0.19	0.12
Floor	0.27	0.1
Windows	2.8	1.4

RENOVATION MEASURES IMPLEMENTATION

The simulation results of the holistic whole-building dynamic energy performance model has shown that the considered office building consumes about 89 kWh/m^2 more primary energy compared to the minimum acceptable numbers set by the BR15 standards. Therefore, different energy renovation measures will be implemented and simulated using the developed dynamic model and the annual energy performance of the office building will be compared to the current building state as a baseline. The renovation measures to be investigated are a mix between deep energy retrofit measures and building systems intelligence improvement measures. The deep energy retrofit measures comply with the regulations set by the BR15 standard for building envelope and components. On the other hand, the measures targeting improving the operation and intelligence of the building systems are in line with the European Standard EN 15232 “Energy performance of buildings – Impact of Building Automation, Controls and Building Management”, particularly the recommendations for control and management of the heating, ventilation and lighting systems. The EN1523 standard came as a support to the EU Energy Performance of Building Directive (EPBD), specifying methods and guidelines to assess the impact of Building Automation and Control System (BACS) and Technical Building Management (TEM) functions on buildings energy performance. In addition, it comprises a structured list of building control, automation and technical management functions to enhance the energy performance. The standard defines 4 BACS Energy Classes as shown in Figure 5, ‘A’ to ‘D’, where ‘A’ represents a building characterized by high BACS and TEM energy performance and ‘D’ represents a building with non-energy efficient or no BACS (EN15232 2007). With no building automation and control system, the considered office case study building in its current state is labelled as Class ‘D’.

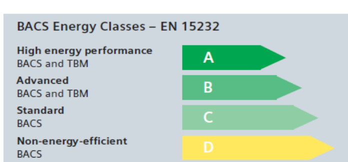

Figure 5 EN 152323 BACS energy classes

Table 5 provides an overview of the different energy renovation measures to be implemented and assessed for the considered case study office building as part of the energy renovation process. In overall, 19 different energy renovation measures are simulated using the developed dynamic energy performance model. Deep energy retrofit measures comprise conventional building physical envelope upgrade including exterior walls and roof insulation and windows upgrade. Moreover, measures targeting building components upgrade, replacement and modification are considered including lights, electric equipment, ventilation fans, heating pumps, heat exchanger unit and PV modules. In addition, measures exhibiting control and management strategies are implemented including daylight sensors, motion sensors, heating setpoint management, demand-controlled ventilation and adaptive heating curve. Using the Parametric Analysis Tool of OpenStudio (PAT 2017), dynamic simulation of the office building energy performance is performed employing different energy renovation measures. In addition, a comparison of the upgraded building energy consumption against the current state baseline model is reported.

Table 5 Energy renovation measures implemented

Energy Renovation Measures		
Type	**No.**	**Measure**
Deep Energy Retrofit Measures	1	Adding 250 mm wall insulation
	2	Adding 300 mm roof insulation
	3	Installing standard triple-glazed windows
	4	Installing triple-glazed windows with low emissivity
	5	Installing efficient constant speed water heating circulation pump
	6	Installing variable speed pump
	7	Installing LED lights
	8	Installing efficient electric equipment
	9	Upgrading the ventilation system supply fan
	10	Installing ventilation system heat recovery unit
	11	Adding 80m^2 PV units on the roof
Building Systems Intelligence Improvement Measures	12	Installing daylight sensors
	13	Installing motion sensors
	14	Management of the heating system setpoint
	15	Implementing temperature-based ventilation
	16	Implementing CO_2-based ventilation
	17	Implementing temperature and CO_2-based ventilation
	18	Implementing demand controlled ventilation
	19	Using adaptive heat curve for weather compensation

Based on the dynamic energy simulations carried out, Figures 6 and 7 shows the holistic technical impact of implementing the different energy renovation measures on the heating and electricity consumption respectively. In the two figures, measure ‘0’ represents the current building status, where measures 1 to 19 are the various renovation measures as denoted in Table 4. The dotted lines in both figures represent the baseline office building respective current heating and electricity consumption to highlight the impacts of each measure.

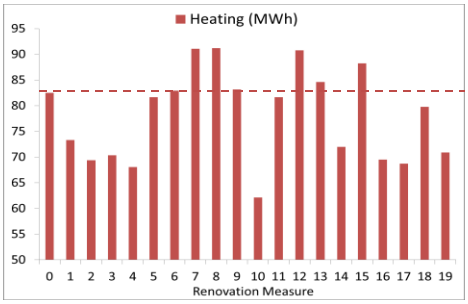

Figure 6 Heating consumption for different scenarios

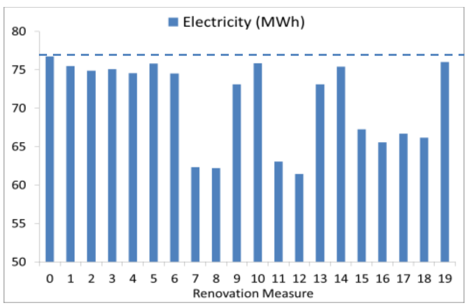

Figure 7 Electricity consumption for different scenarios

As shown in Figure 6, there is a large variation in terms of the impact of the different renovation measures on the office building overall heating consumption. Thus, an increase in the heating consumption is exhibited in 7 out of 19 measures, with replacing lights and electric equipment and installing daylight sensors resulting into the highest addition on the heating consumption. This is due to the fact that new LED lights and efficient equipment in addition to controlling the lights operation using daylight sensors would lead to less heat losses from these devices and thus resulting into higher heat demand. On the other hand, adding a heat recovery unit to the ventilation system is found to provide the most significant heating savings up to 25%. In addition, the deep physical envelope retrofit measures (1 to 4) result into heat savings ranging from 11% to 17%, where other management and control measures would result into similar savings including, 13% for management of heating system setpoint, 17% for CO_2-based ventilation system control implementation and 14% for using adaptive heat curve for weather compensation. Regarding the impact on the electricity consumption, it is shown that all the renovation measures implemented would lead to a reduction on the overall electricity consumption at different levels. The measures with the highest impact on decreasing the electricity demand are LED lights, efficient equipment, PV units and installing daylight sensors, in addition to the measures (15 to 18) targeting control and management of the ventilation system operation, leading to savings ranging from 12% to 15%. On the other hand, some other measures including fans and pumps upgrade result into minor savings on the electricity consumption (1 to 5%), but could be considered viable especially from the economic perspective. The simulation results presented show that both deep energy retrofit measures along with measures targeting improving energy systems intelligence could prove a viable option and provide the added value in terms of improving the office building energy performance and reducing overall heating and electricity consumption. Nevertheless, 3 additional renovation packages are investigated and simulated, each comprising a list of selected energy renovation measures from the 19 measures presented in Table 4. In this context, Package 1 is a purely deep energy retrofit package with 9 measures: wall and roof insulation, triple-glazed windows, variable speed heating pumps, LED lights, efficient equipment, ventilation fan upgrade and implementing a ventilation heat recovery unit. Package 2, is an extension to Package 1 with only one measure added which is installing 80m^2 PV system on the office building roof. Package 3 is a package targeting building intelligence with 5 measures for energy systems control and management including daylight sensors, motion sensors, demand-controlled ventilation, thermostat heating setpoint management and the implementation of an adaptive heating curve. The three renovation packages were implemented and simulated using the dynamic holistic energy model.

Table 6 Energy renovation packages implementation

	Base Case	**Pack 1**	**Pack 2**	**Pack 3**
Measures Implemented	-	1, 2, 4, 5, 6, 7, 8, 9, 10	1, 2, 4, 5, 6, 7, 8, 9, 10, 11	12, 13, 14, 18, 19
Heating (MWh)	82.5	48.2	48.0	65.6
Lighting (MWh)	24.4	9.9	9.9	7.6
Ventilation (MWh)	13.1	7.2	7.2	2.3
Equipment (MWh)	39.2	22.5	22.5	39.0
Annual Primary Energy (kWh/m^2)	228.6	115.2	71.1	120.5

Table 6 provides an overview of the different renovation packages impact on the holistic office building energy consumption. In addition, Figure 8 shows the annual primary energy consumption in each case compared to the BR15 Danish Renovation Classes in the building regulation. It is shown that the deep energy retrofit Package 1 would allow saving around 41.6% on the heating consumption and 48.5% on the electricity consumption, with an overall saving of 49.6% on the annual primary energy consumption. Thus implementing renovation Package 1 will allow the office building to comply with the BR15 Renovation Class 2. Moreover, adding a PV system to the deep energy retrofit mix in Package 2 would lead to a further decrease of primary energy consumption by 68.8% to only 71.1 kWh/m^2 and thus the office building would comply with the more strict BR15 Renovation Class 1. On the other hand, implementing the renovation Package 3 with techniques and strategies to control and manage the heating, lighting and ventilation systems would lead to respective savings on heating and electricity consumption of 20.6% and 36.4%. Through the implementation of various building intelligence improvement measures, Package 3 will allow the office building to comply with the Renovation Class 2 with a primary energy consumption of 120.5 kWh/m^2. In addition, this package will enhance the office building rating according to the EN 152323 BACS energy classes from Class 'D' to Class 'B' in terms of energy systems operation and building intelligence.

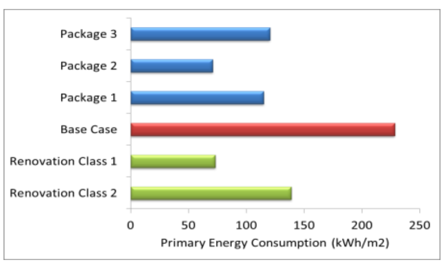

Figure 8 Annual primary energy consumption

Based on the simulation results presented, it is shown that both packages, the deep energy retrofit Package1 and the building intelligence improvement Package 3 would allow a significant reduction in the annual building primary energy consumption to comply with the BR15 Renovation Class 2. Therefore, both options seem viable from the technical perspective with large potential of savings on heating and electricity. However, Package 3 provide the capability to raise the building intelligence rating to 'B' according to the EU 152323 standard which could prove to be significantly important if the standard became mandatory for public buildings. Nevertheless, an additional renovation 'Holistic Package' was investigated and assessed which is a combination of Packages 2 and 3 with deep energy retrofit measures, building energy systems intelligence improvement and renewable PV system addition. This holistic renovation package was simulated through implementing the whole measures in the dynamic model developed. Table 7 shows that the holistic renovation package could reduce heating and electricity consumption significantly by 56.7% and 63.8% respectively. In overall, the primary energy consumption in this case is reduced to only 44.6 kWh/m^2, just above the expected primary energy of a similar new office building with the same interior area, complying with BR15 standards for new buildings with a primary energy consumption of 42.25 kWh/m^2.

Table 7 Holistic renovation package implementation

	Base Case	**Holistic Package**
Heating (MWh)	82.5	35.7
Lighting (MWh)	24.4	3.3
Ventilation (MWh)	13.1	1.6
Equipment (MWh)	39.2	22.8
Primary Energy (kWh/m^2)	228.6	44.6

CONCLUSION

In this study, the trade-off between deep energy retrofit and improving building intelligence within an energy renovation process was investigated and assessed from the technical perspective. A case study was considered with 800m^2 standard Danish office building from the 1980's. A holistic detailed energy model was developed using EnergyPlus and the building dynamic performance simulation results show a large potential for energy renovation and performance improvement. Thus, 19 renovation measures were implemented and simulated including deep energy retrofit measures and measures to improve the building intelligence through energy supply systems control and management strategies. Using the measures, 3 renovation packages were developed and investigated and it was found that both deep energy retrofit package and building intelligence improvement package allow the building to comply with the BR15 Renovation Class 2 with primary energy savings of 49.6% and 47.2% respectively, with the latter allowing the building to comply with the Class 'B' of the EN 152323 BACS standard. In addition, it was shown that employing a holistic energy renovation package with combined deep energy retrofit and building intelligence improvement measures will lead to significant reduction on heating and electricity consumption by 56.7% and 63.8% respectively. In this case, the renovated building performance becomes very close to a similar newly built building complying with BR15 regulations. From the technical perspective, the results presented in this paper demonstrate that significant savings could be attained in renovating Danish office buildings, either by implementing a deep energy renovation package or by improving building intelligence. However, various factors need to be considered in the renovation strategy decision-making including the building age, physical building envelope condition, type of energy supply systems, level of building automation and control. In addition, the economic feasibility of the renovation process is a major factor in the decision-making phase and shall be considered with the same importance as the technical impact. Moreover, the results of implementing the holistic renovation package in this study shows that it is wise to consider a combined approach in building renovation with a mix of measures targeting building physical envelope, equipment and auxiliaries, renewable energy units, and energy supply systems management and control strategies. Such approach will lead to a building complying with the Danish building standard and with the EU automation and control regulations. This study forms a basis for the development of a complete energy renovation decision-support tool to identify the most energy efficient and cost-effective balance of measures to improve existing buildings performance.

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