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TECHNICAL AND ECONOMIC ASSESSMENT OF A DANISH PUBLIC SCHOOL ENERGY RENOVATION USING DYNAMIC ENERGY PERFORMANCE MODEL

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ABSTRACT

This study targets the public schools sector in Denmark, considering a case study of an 11,900 m^2 School in Odense, and reporting the overall process of energy modeling, performance simulation and assessment of renovation measures. A holistic model was developed and calibrated using measured energy data. Various energy renovation measures and packages were investigated employing a holistic approach and considering the technical, economic and environmental impacts. A deep energy renovation package was recommended lifting the school energy rating to comply with the BR15 Danish building regulations, reducing energy consumption by 54.2% with an annual primary energy consumption of 65.5 kWh/m^2.

INTRODUCTION

In the recent years, Denmark has established itself as a role model country with high life standards and stable economic sector accompanied with an efficient energy sector and decreasing greenhouse gas emissions. Yet, Denmark has set an ambitious holistic goal of eliminating the use of conventional fossil fuel-based energy resources and having an energy sector relying 100% on renewable energy by 2050 (Lund and Mathiesen 2009). In this context, energy efficiency regulations and policies have been developed aiming to implement efficient technologies and expand the use of renewable energy systems in addition to setting a strict climatic objective to reduce the greenhouse gas emissions by 90% in 2050 compared to 1990 numbers. On the level of the building stock, the Danish government has highlighted the potential of improving the energy performance of newly built buildings with strict and tightened requirements. Figure 1 shows the maximum allowed annual primary energy consumption of a standard 150 m^2 building based on various Danish building regulations throughout the years (Energy Efficiency in New Buildings 2015). With around 75% of the current Danish buildings being built before the 1980, the figure demonstrates the large potential to carry out a large-scale energy renovation to improve the energy performance of the existing building stock. Therefore, the government has developed a comprehensive "Strategy for energy renovation of the existing building stock" (Strategy for Energy Renovation of Buildings 2014), with multiple initiatives aiming to drive an overall cost-effective and energy-efficient renovation process for existing buildings across the country.

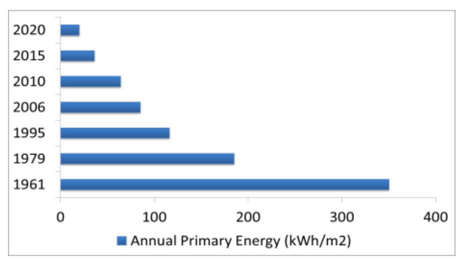

Figure 1 Maximum annual primary energy consumption in a standard building

The Danish Building and Urban Research Unit has prioritized three energy renovation measures for Danish buildings built between 1960 and 2004 (Tommerup and Svendsen 2006): insulating exterior walls, installing efficient windows and upgrading the ventilation system. In a recent study, Nielsen et al. (2016) highlighted the importance of adopting a systematic screening of various energy measures for Danish buildings energy renovation, considering economic and technical factors. While the majority of studies concerning energy renovation has targeted Danish residential buildings and houses (Bjørneboe et al. 2017), different Danish municipalities have realized recently the importance of implementing large-scale projects to renovate existing public and administrative buildings around the country. The energy renovation of four administrative and public buildings in Denmark was reported and assessed by Rose and Thomsen (2015). Two office buildings, Rockwool Office Building and Parkvænget Office Building in addition to the Osram Culture Centre and Vejtofen Kindergarten have undergone a deep energy renovation process including walls and roofs insulation, efficient windows, controlled-ventilation system with heat recovery unit, LED lights, efficient heat pumps and solar thermal and PV units, resulting into savings in the range of 45-85% on the overall energy consumption. Another office building that was renovated lately is Vester Voldgade 123 (Danish Building and Property Agency 2015), which was labelled after renovation as the world's largest certified passive house with energy savings up to 76%. In addition, Jradi et al. (2017) presented an overall technical assessment of the energy renovation process of the Mærsk Office Building in Denmark, where a deep energy renovation package along with solar PV system was implemented reducing energy consumption by 51%. On the other hand, very few studies were presented targeting public schools sector, although the majority of public schools in Denmark were built in the period between 1940 and 1970 with no major renovation process carried out.

With the aim to attain a CO_2 neutral city by 2050, Odense Municipality has established the Energy Lean project with an investment of 225 million DKK aiming to reduce energy consumption in public schools and decrease CO_2 emissions by 40% (Odense Energy Lean 2016). In collaboration with Odense Municipality and under the international research project COORDICY (COORDICY 2018), this study targets the public schools sector in Denmark, aiming to implement a methodical and systematic approach for energy modeling, performance simulation and renovation evaluation of Danish public buildings using a holistic dynamic energy performance model allowing multi-objective energy renovation assessment considering technical, economic and environmental impacts. Seden School, an 11,900 m^2 public school in Odense, is considered as a case study where the overall methodology and process of energy modeling, performance simulation and assessment of energy renovation measures is reported. A holistic energy model for the school is developed, consisting of 12 blocks, employing a package of Sketchup and OpenStudio modeling tools and EnergyPlus simulation engine, taking into account different school characteristics including constructions, specifications, occupancy behavior, schedules and energy supply systems. The base energy model is calibrated using actual measured energy data. In addition, field visits, energy supply systems inspections and interviews with the technical managers and users are conducted. Based on the information collected, various energy renovation measures and packages are investigated, implemented and assessed, employing a holistic approach and considering the technical, economic and environmental impacts of each package.

HOLISTIC MODELING AND SIMULATION APPROACH

The trend in the majority of energy renovation applications across Denmark is still a building renovation process driven by the need to modify or upgrade the building components with no systematic methodology implemented and the absence of an overall technical, economic and environmental assessment of various approaches in the decision-making phase (Friege and Chappin 2014). In addition to this 'reactive' approach in renovation projects, BE15 is the official building energy modelling, simulation and assessment tool in Denmark which uses a static and simplified modelling and simulation approach to assess the building performance (BE15 2015). While this assessment is useful in terms of carrying out fast and simple preliminary building performance evaluation, it is subject to major uncertainties as the tool considers the whole building as a single large thermal zone with default schedules and systems operation patterns and without taking the impact of climatic conditions and occupancy behavior into account. In terms of energy renovation, the tool capability is limited to a static evaluation of each modification in the building physical envelope independently. However, to consider interdependencies and integration of various building components and to take into account the impact of weather conditions and occupancy behavior, this study adopts a new modelling, performance simulation and energy renovation methodology based on a holistic design approach to fully represent various interdependencies and dynamics in the building operation and carry out a holistic assessment of the technical, economic and environmental impacts of various renovation measures and packages.

As a basis for the overall building energy modelling, simulation and renovation assessment, a holistic dynamic energy performance model is developed considering various building specifications and characteristics including location and geometry, physical envelope and constructions, occupants behavior, energy supply systems and operation strategies, equipment, schedules and climatic conditions. Figure 2 provides an overview of the overall methodology for energy modelling, simulation and renovation assessment implemented in this study. A package of Sketchup Pro, OpenStudio and EnergyPlus tools is employed in various phases of the developed methodology. Sketchup Pro is used to draw the overall 3D architectural model using information on the building location, geometry and physical envelope. The 3D model is used as an input in the OpenStudio tool where the major components of the holistic dynamic energy performance model are developed considering different building characteristics and specifications. OpenStudio is used for the model development as it provides a user-friendly interface allowing flexible and detailed definition of physical envelope constructions, energy supply systems, loads, schedules and operation strategies. As the dynamic model is developed, the EnergyPlus simulation engine is used as a basis to run an annual dynamic simulation of the holistic building energy performance. In addition, the holistic model will be calibrated employing actual measured data from the site using the OpenStudio Parametric Analysis Tool (PAT 2017). The calibrated model will then be used to implement various renovation measures including physical envelope upgrade and measures to improve energy systems control and management. In addition, different renovation packages will be implemented and assessed against the base case situation from the technical, economic and environmental perspective, where recommendations will be highlighted to aid the energy renovation process decision-making.

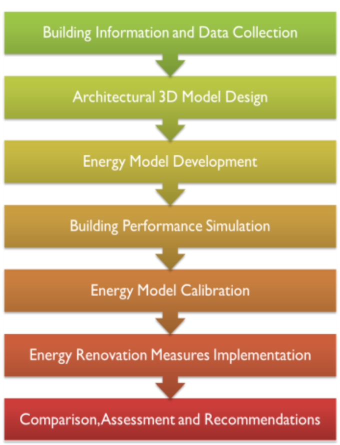

Figure 2 Overall building energy modelling, simulation and renovation assessment methodology

CASE STUDY

Aiming to improve the overall energy performance and cut the energy consumption of public schools, Odense Municipality, the third largest city in Denmark, has launched the 'Energy Lean' project with an investment of 225 million DKK to carry out a large energy renovation process for public schools all around the city. In collaboration with Odense Municipality, Seden School is one of the schools considered as a case study under the international research project COORDICY to implement a holistic and systematic energy modelling, simulation and renovation assessment methodology aiming to provide recommendations to aid the school energy renovation process. In this study, the overall process of Seden School building blocks energy modelling, performance simulation and renovation assessment of various measures and packages is reported and presented in the next sections. Seden school is an elementary school which constitutes currently of 12 building blocks spanning across an area of 11900 m^2, where blocks 1 and 2 are shown in Figure 3. In Fall 2017, the school had 640 students and 28 full-time teachers. The school was initially built in 1955 with the establishment of blocks 1, 2, 8 and 10. Then, blocks 4, 5, 6 and 7 were added in 1968 and block 9 was established in 1975 along with a sports arena (block 13) and two SFO blocks for after school services and activities (blocks 14 and 16). A plan view of the school blocks with their respective geometry is shown in the developed Sketchup plan drawing in Figure 4.

Figure 3 Seden school blocks 1 and 2

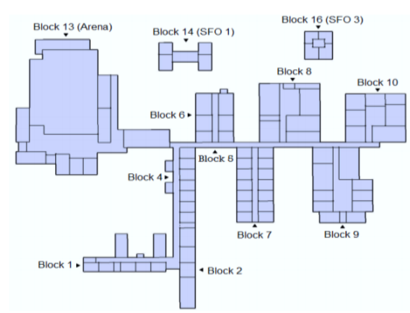

Figure 4 Plan view of the Seden school blocks

The modelling and simulation methodology illustrated in the previous section was implemented in the case of Seden School. The first working phase in terms of collecting information and data regarding the building geometry, envelope, specifications, systems and various components was a relatively long process, considering that some information dates back to the 1955 when the school was established. This includes reviewing architectural drawings, energy systems and design specifications, materials and constructions information, multiple field visits to the different school blocks, technical investigation of energy systems, and interviews with technical managers and users. Using information collected regarding the blocks location geometry, space allocation and orientation, a 3D architectural model for the school was developed in Sketchup Pro with the 12 blocks as shown in Figure 5.

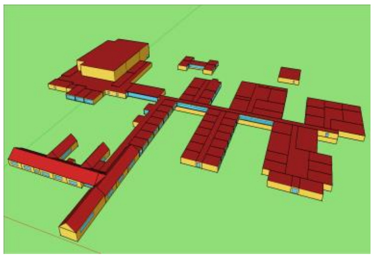

Figure 5 Seden school 3D Sketchup model

Table 1 Seden school physical envelope characteristics

Blocks	Exterior Walls	Roof	Floor	Windows
1 and 2	300mm brick with 75mm mineral wool	120mm brick with 200mm mineral wool	100mm concrete with 50mm leca	Single-glazed windows with 4.8 W/m^2.K U-value
4, 5, 6, 7, 8, 9 and 10	120mm lightweight concrete with 50mm mineral wool	120mm brick with 100mm mineral wool	100mm concrete with 50mm leca	Double-glazed windows with 2.7 W/m^2.K U-value, Skylights are triple-glazed
13	300mm brick with 75mm mineral wool	120mm brick with 100mm mineral wool	100mm concrete with 50mm leca	Double-glazed windows with 2.7 W/m^2.K U-value
14	100mm wood with 100mm mineral wool	30mm roofing felt with 75mm mineral wool	50mm concrete with 100mm mineral wool	Double-glazed windows with 2.7 W/m^2.K U-value
16	100mm wood with 150mm mineral wool	30mm roofing felt with 75mm mineral wool	50mm concrete with 100mm mineral wool	Double-glazed windows with 2.7 W/m^2.K U-value

Table 1 provides an overview of the school blocks physical envelope constructions and materials. In addition, Table 2 presents main information regarding the HVAC system components and operation in the different blocks. In overall, all the 12 school blocks investigated are connected and served by direct district heating loop to fulfil heating demands via radiators in different rooms. Hot water is produced in the basement with a storage buffer tank. The overall heating system is controlled centrally using a CTS system based on the heating setpoint in each block. Various types of mechanical ventilation systems with variable capacities are implemented to serve the different blocks as highlighted in Table 2 where block 2 is the only block which is naturally ventilated. Regarding the lighting system, two major light types are used, T5 and T8 tubes with some motion sensors installed in certain rooms.

Table 2 Seden school HVAC systems specifications

Blocks	Ventilation System Type	Air Flow Rate (m^3/h)	Heating Setpoint (°C)	Schedule (h)
1	Exhausto VEX3.5 with CFH*	1440	21	2x20 min a day
2	Natural Ventilation	-	18	
4	KCA	3100	21	7-15
6	KCA	2880	21	7-15
7	KCA	3890	21	7-15
8	NV ZE-3-CL	4000	21	7-15
9	NV ZE-3-CL	5000	21	7-15
10	NV ZE-3-CL	3300	21	7-15
13	Fläkt	15550	18	6-22, Sat-Sun 7-22
14	Exhausto VEX4.5 with CFH*	5190	21	6:30-8 & 14-16:30
16	3xExhausto VEX1.5 with CFH*	1245	21	2x2 hours a day

*CFH: Cross-flow Heat Exchanger

SEDEN SCHOOL MODELING AND SIMULATION

The school 3D model developed in Sketchup was introduced to the OpenStudio where various information collected regarding the school physical envelope, constructions, energy supply systems, HVAC components, equipment and lights, occupancy, loads and schedules are defined in details to develop a school holistic energy performance model. An updated weather file was created and imported in OpenStudio, with actual weather conditions for Odense including ambient temperature, wind speed and solar radiation. After the 3D model creation in Sketchup and the detailed energy performance model development in OpenStudio, the validated EnergyPlus simulation engine is used to run an annual energy performance simulation of Seden school and predict energy consumption at different levels. In addition, the holistic energy model was calibrated using actual collected data from energy meters implemented onsite. The OpenStudio parametric analysis tool was used as a basis for model calibration using a holistic parametric approach based on the methodology developed by Hale et al. (2014). Actual monthly energy consumption of heating and electricity in addition to actual weather conditions data and reported occupancy schedules were introduced in the parametric analysis tool and multiple simultaneous energy simulations were carried out, with the variation of selected parameters including infiltration rates, lighting and equipment schedules, devices and components efficiencies, air flow rates and operational setpoints. Around 150 combinations of different scenarios were simulated and the combination having consumption results with the lowest deviation compared to the monthly actual energy consumption meters is selected to serve as a calibrated school dynamic energy performance model. It was shown that the calibrated energy model predicts the overall monthly energy consumption of the school with an acceptable error of 1.7% and 2.2% for annual heating and electricity consumption respectively. Figures 6 and 7 show the monthly overall heating and electricity consumption of Seden school with a comparison between actual and simulation consumption results. In addition, Fig. 8 shows a breakdown of the annual overall energy consumption in Seden school. Heating contributes to the largest share in the consumption with 85.7% and around 1720 MWh, where the rest is electricity consumption in the form of ventilation (5.8%), equipment (5.2%) and lighting (3.4%).

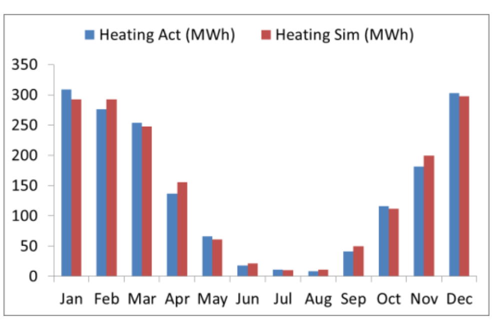

Figure 6 Heating energy consumption Act vs Sim

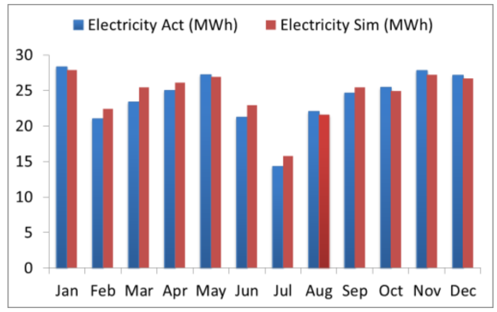

Figure 7 Electricity consumption Act vs Sim

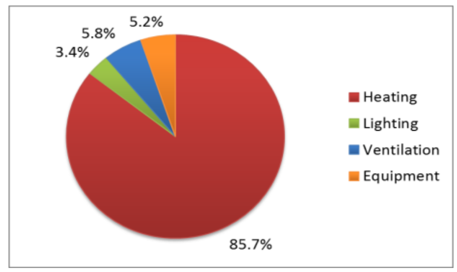

Figure 8 Seden school energy consumption breakdown

Table 3 presents Seden school annual primary energy consumption, calculated based on the BR15 Danish building regulation and accounting for heating, ventilation, lighting, domestic hot water and building services, excluding electric equipment consumption. The annual primary energy consumption of Seden school in its current state is found to be around 192.5 kWh/m^2. As shown in Table 3, if the school is going to be renovated and comply with the BR15 building regulations, it should consume less than 135.26 kWh/m^2 to comply with Renovation Class 2 and less than 71.43 kWh/m^2 to comply with the more strict Renovation Class 1. Moreover, if a similar new modern school is to be built today having the same interior area, the maximum allowable annual primary energy consumption of such school is only 41.1 kWh/m^2. The numbers provided in the table demonstrates the large potential to carry out an overall energy renovation process at Seden school to improve the energy performance and cut energy consumption drastically.

Table 3 Seden school primary energy consumption vs BR15 standards

	Primary Energy Consumption (kWh/m^2)
Seden School current state	192.5
BR15 Renovation Class 2	135.26
BR15 Renovation Class 1	71.43
BR15 for similar new school	41.1

RENOVATION MEASURES IMPLEMENTATION

The overall dynamic energy performance simulation of the Seden school different blocks has shown that there is a very large potential to carry out a systematic full-scale energy renovation process, where the building annual primary energy consumption shall be reduced by at least by 58 kWh/m^2 in order to comply with the acceptable standards of BR15 Renovation Class 2, and further by 121 kWh/m^2 to comply with the highest Renovation Class 1. Therefore, various energy renovation measures have been investigated and simulated on the level of each single block in the school using the developed calibrated dynamic energy performance model. The renovation measures investigated are presented in Table 4, with a mix of measures to improve the physical envelope of the school and measures to enhance different energy supply systems operation in addition to control and management techniques. The renovation measures considered are: 1) external wall insulation, 2) roof insulation, 3) triple-glazed windows, 4) LED lights, 5) daylight sensors installation, 6) motion sensors installation, 7) upgrade of heating circulation pumps, 8) upgrade of ventilation system supply fan, 9) addition of a ventilation system heat exchanger, 10) implementation of demand-controlled ventilation (DCV), 11) heating setpoint management, and 12) installation of PV units to cover 5% of the roof area.

Table 4 Energy renovation measures implemented

Number	Renovation Measure
1	External Wall Insulation
2	Roof Insulation
3	Triple-Glazed Windows
4	LED lights
5	Daylight Sensors
6	Motion Sensors
7	Efficient Variable Speed Pumps
8	Efficient Ventilation System Fan
9	Ventilation Heat Exchanger
10	Demand-Controlled Ventilation
11	Heating Setpoint Management
12	Photovoltaic System

All of the 12 renovation measures were implemented first on the level of each single block. It shall be mentioned that some measures are inapplicable for certain blocks and thus are not considered, for example the ventilation system heat exchanger as some blocks already have a ventilation system with an implemented heat exchanger. Tables 5 and 6 show the impact of renovation measures 1 to 10 for Blocks 7 and 10 respectively, from the technical, economic and environmental perspective. It shall be mentioned that measures 11 and 12 are implemented on the level of the whole school. Due to the pages limit, only results for blocks 7 and 10 are presented in this study, but they can be considered representative for the other blocks performance under various renovation measures. Based on the simulation results presented, it is shown that conventional physical envelope measures (1 to 3) yield major energy savings, with the roof insulation seems the top priority yielding the largest savings. However, it is noted as well that targeting the ventilation system in the different blocks is profitable and shall be prioritized, where the two measures yielding the highest heating savings are adding a ventilation heat exchanger unit and implementing DCV to manage the ventilation system operation. Those two measures are also the respective measures with the highest operational cost savings and CO_2 emissions reduction. In addition, upgrade of the ventilation system supply fans is shown to provide significant energy and operational cost savings as well. As electricity is much more expensive than heat (2 DKK/kWh electricity compared to 90 DKK/GJ heat consumption), it is more profitable to target measures that could save electricity consumption, including LED lights and installing daylight sensors, although such measures increase heating consumption relatively due to less heat losses from highly efficient LED lights compared to the current fluorescent tubes. Moreover, upgrading the heating circulation pump is found to have limited impact on energy savings compared to other measures, yet could prove feasible due to the low investment cost and simple measure implementation. From the environmental perspective, it is shown that roof insulation, ventilation heat exchanger addition and DCV implementation yield the highest amount of CO_2 emission savings.

Table 5 Impact of renovation measures on Block 7

Measure	Electricity Savings (kWh)	Heating Savings (kWh)	Cost Savings (DKK)	Emission Savings (kg.CO_2)
1	603	5933	3123	623
2	1576	19721	9523	1939
3	492	4265	2362	466
4	4245	-2102	7811	1153
5	3661	-1657	6787	1006
6	1701	-692	3179	473
7	1938	-628	3672	550
8	4857	-1379	9268	1394
9	409	74738	24958	5634
10	8359	71374	39773	7835

Table 6 *Impact of renovation measures on Block 10*

Measure	Electricity Savings (kWh)	Heating Savings (kWh)	Cost Savings (DKK)	Emission Savings (kg.CO_2)
1	297	4070	1910	392
2	1104	16274	7464	1539
3	381	4487	2211	448
4	3244	-1768	5917	869
5	2883	-1379	5320	786
6	1145	-414	2157	322
7	1521	-573	2856	426
8	4023	-1129	7681	1156
9	270	30980	10546	2366
10	8026	13744	20491	3485

On the other hand, no single measure of the 10 measures implemented could prove feasible alone to reduce the school energy consumption to an acceptable level to comply with the BR15 standards. Considering this, in addition to the school age and current situation of the physical envelope and energy supply systems, a deep energy renovation process is indispensable. Thus multiple energy renovation packages are developed using the 12 measures, and considering a large number of combinations. The renovation packages were simulated in parallel using the calibrated dynamic energy model and employing the OpenStudio PAT. Table 7 provides an overview of 7 selected renovation packages with measures breakdown, annual energy savings, cost savings and emissions reduction attained.

Table 7 Energy renovation packages implementation

PACK	Measures	Energy Savings (%)	Cost Savings (%)	Emission Savings (ton.CO_2)
A	8,9,10	38.4	52.5	75.2
B	7,8,9,10	38.6	60.0	83.1
C	1,2,3,4,9,10	52.2	67.1	98.0
D	3,4,5,9,10	41.1	59.3	83.5
E	1,2,3,4 11, 12	43.2	58.9	84.3
F	1,2,3,4, 10, 11,12	48.8	64.2	93.1
G	1,2,3,4, 9,10,11,12	54.2	69.3	101.4

It is shown that the overall energy consumption savings attained ranges from 38% to 55%, along with significant savings on the school operational cost in the range of 52-70%. From the environmental perspective, the renovation packages will lead to a reduction between 75 tons and 102 tons on the CO_2 emissions. Package G is a holistic whole school deep energy renovation package with 8 energy improvement measures on the level of the building physical envelope and energy supply systems as follows: wall insulation, roof insulation, triple-glazed windows, LED lights, ventilation system heat exchanger, demand-controlled ventilation implementation, heating setpoint management and installation of PV units to cover 5% of the roof area. The dynamic energy simulations show that implementing renovation package G would decrease Seden school overall energy consumption by 54.2%, the school operational cost by 69.3% and a significant reduction of 101 tons on CO_2 emissions annually. In addition Figure 8 shows the annual primary energy consumption of the school per heated floor area in the case of each of the renovation packages. Compared to the current school situation, all the packages from A to F allow reducing the primary energy consumption so the school will comply with the BR15 Renovation Class 2. Nevertheless, the deep energy renovation package G will reduce primary energy consumption to only 65.5 kWh/m^2 and thus the school will comply with the highest energy standard Renovation Class 1 for existing buildings.

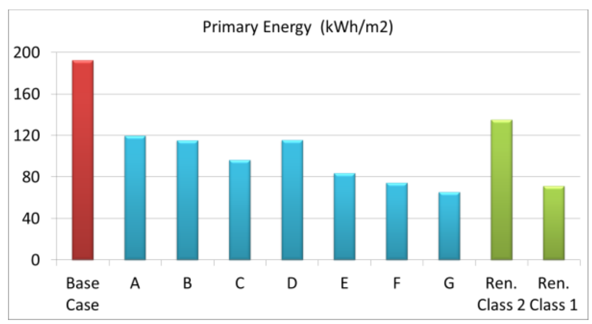

Figure 8 Primary energy consumption for different packages

Although the deep energy renovation package G proves to have significant savings on energy, operational cost and emissions, the investment cost of this package is relatively high with a large number of renovation measures included. The measures targeting energy systems improvement including the installation of ventilation system heat exchanger unit and using LED lights are considered cost-effective with short payback periods compared to measures targeting the school physical envelope including wall and roof insulation and windows replacement, which are characterized by relatively longer payback periods. However, considering the importance of the school indoor thermal comfort and air quality based on the users feedback and recognizing the need to upgrade the school envelope constructions to comply with the BR15 regulations, an overall deep energy renovation package is indispensable, comprising physical envelope upgrade and energy systems improvement measures. Such package will save energy, cut operational costs, reduce CO_2 emissions and allow the school to comply with the BR15 standard in terms of energy consumption and physical envelope components.

CONCLUSION

In this study, the overall process of energy modeling, performance simulation and energy renovation assessment of Seden school in Odense, Denmark is investigated and presented. A holistic and systematic approach is considered with a detailed dynamic energy performance model as a basis. The developed school dynamic energy model was calibrated using actual measured energy consumption data onsite. The primary energy consumption of the school in the current state was found to be around 192.5 kWh/m^2, around 58 kWh/m^2 more than the maximum limit allowable for the school to comply with the standards of BR15 Renovation Class 2. Twelve different energy renovation measures were implemented and simulated in the model on the level of each school block. Using these measures, different energy renovation packages were developed and investigated, reporting the technical, economic and environmental impacts in each case. Based on the energy simulation results, a deep energy renovation package was selected and recommended with a combination of measures to upgrade the building physical envelope constructions and improve the energy supply systems operation and management. This will allow 54.2% reduction on the annual overall energy consumption, and around 69.3% on the operational cost with a significant reduction of 101 tons on CO_2 emissions. The results of this study will serve as an overall evaluation, assessment and recommendation to support the decision-making process for the Seden school renovation by 2018. The energy performance and indoor thermal comfort and air quality in the different school blocks will be monitored and reported as part of the energy renovation process post-assessment under COORDICY research project.

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