Future Cities and Environment

Design, Modelling and Performance Evaluation of a Positive Energy District in a Danish Island

TECHNICAL ARTICLE

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ABSTRACT

Nowadays, cities and districts are becoming more and more interconnected in terms of energy supply systems, and the transition towards smart connected thermal and electrical grids is inevitable. While single building-level modelling has demonstrated numerous technical and economic benefits, it is vital to scale up the approach and consider the larger picture of cluster of buildings, districts, and cities. The island of Ærø in Denmark has an ambitious goal to become the first CO_2 neutral and renewable energy self-sufficient Danish Island by 2025, as well as becoming a fossil-fuel free island by 2030. With the ambitious energy and environmental aims of Ærø island, this work aims to investigate the capability of establishing part of the island as the first Danish positive energy district (PED) and assess various design scenarios and possibilities of upgrading/modifying the current scheme and composition of energy supply and distribution. An open-source urban scale modelling tool is used, City Energy Analyst (CEA), where the district is modelled considering all specifications and characteristics of buildings and the corresponding energy supply systems. The base case scenario is simulated, and the performance is calibrated using actual data. Then, multiple energy improvement measures targeting the buildings envelope as well as the energy generation and supply systems are developed and simulated to assess the impact on the overall energy consumption for heating and electricity. The results show that a PED can be established employing an improvement package of envelope-targeting measures, energy systems upgrades and renewable energy systems expansion.

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INTRODUCTION

To reduce the greenhouse gases (GHG) emissions, the European Commission (EC) has set a long-term strategy to implement sustainable solutions in the pursue for a net zero GHG emission in the EU by 2050 (European Commission, 2019). One of the key milestones in this plan is to improve the energy efficiency in buildings, as they are responsible for 40% of energy consumption and around 35% of the emissions (EC, A, 2018). Considering this contribution to both energy consumption and greenhouse gas emissions, it is vital to improve the design and setup of newly built buildings in addition to enhancing the performance and operation of existing buildings through systematic energy efficient and cost-effective retrofitting processes. Thus, the EU has pledged to attain an overall 55% carbon reduction, compared to 1990, by 2030 (European Union, 2021).

A large body of theoretical and experimental work was devoted to enhancing the level of buildings control and management and optimization of the overall energy performance (X. Li, 2014) (M. Jradi, 2018) (A.A.A. Gassar, 2020). In this context, dynamic energy modelling and simulation has served as a key approach towards realizing the impacts of improving the building stock energy performance and reporting the added value on the technical, economic and environmental levels. Employing accurate building models and predictions, better building designs have been delivered, both for newly built buildings and retrofitted buildings, and the building response to various dynamic changes within the building environment was assessed and analysed from different perspectives (M. Jradi, 2018) Generally, building energy modelling has been used extensively in the literature as a tool for better design, operation and optimization of buildings performance. Overall, energy modelling and simulation of the performance of single buildings and facilities is a very well mature domain and readily available commercial tools are widely used allowing accurate building modelling and performance predictions. In terms of the economic feasibility of using building energy modelling, it was reported that the development of a detailed building dynamic energy model has an overall payback period of around 1–2 months (HOK, 2016). Such short payback period supports the use of such model-driven approaches to aid decision-making in the context of designing, operating, controlling, and commissioning of new and existing buildings.

In the recent years, there has been a growing number of studies and investigations dealing with energy modelling, analysis and performance optimisation of urban areas, districts, and cities (Ali, et al., 2021). The complexity of building cluster simulations is addressed by Eicker in "*Urban energy systems for low carbon cities*" and it is assessed that the most accurate cluster models need many inputs and often the predictions are not as accurate as single building models, as it is hard to schedule human behaviour, urban climate, and characterize the complexity of a single building on a larger basis. (Zhengwei Li, 2016) (Eicker, 2019).

The approach of dealing with building clusters is still a relatively unmature domain and therefore there are no validated standard procedures when modelling large building clusters. This affects the prediction accuracy and hinders direct comparisons. (Eicker, 2019,). Lately many different cluster models and methodologies for predicting energy consumption of building districts and cities on small/medium scale level have been developed i.e., CitySim, UrbanSim "UCB", Urban Modelling Interface "UMI" and City Energy Analyst "CEA". All these tools estimate the energy demand of an area dependent on the surroundings, area and climate (Marcel Bruse, 2015) (Alaia Sola, 2020) (Fonseca, 2016).

Shi et al. (Shi, 2017) has reviewed different methods, and developed a workflow for an optimization model of an urban design, consisting of three steps; the data collection step, the generation step where the urban design and constraints are introduced, and the optimization step where the energy performance is improved and the optimal solution is found. Delmastro et al. (Delmastro C., 2015) reported that when considering building clusters and areas for analysis, the energy consumption of the forming building stock is affected by multiple factors. This includes the design of the built environment under investigation, the interaction between the buildings and open spaces in the district, the building envelope and constructions, the socio-economic characteristics of the population in the specific area, the type of shades and obstructions available, and most importantly, the weather conditions.

One of the recent initiatives towards improving the energy performance of cities and districts on a large scale is the establishment of the so called 'Positive Energy Districts' (PED) (Lindholm O, 2021). The basic principle of PEDs is the establishment of an area within the boundaries of a city or large district, which is capable of producing more energy than consumed on a yearly net level. In this regard, such areas are flexible enough to dynamically respond to the stochastic variation of the energy market, in addition to supporting the minimization of the impact on the connected centralized energy networks. This is established using alternative decentralised solutions, renewable energy systems, energy storage techniques and better control and management patterns. Aiming to attain the energy and environmental goals in the EU, the EU Commission has proposed generic regulatory conditions to support the implementation of Positive Energy Districts in real urban concept by 2050. Although they bring numerous technical and economic benefits, PEDs are still in the early development stage, and the goal for achieving a pure PED is still more an aim than a reality. Nevertheless, the EU has launched a project aiming to plan and develop a hundred PEDs by 2025 (Monti, 2016) (Planet, 2020). This could be a major driver towards establishing such PEDs in Europe as well as in the rest of the world regions.

Nevertheless, most theoretical investigations and practical applications developed in the recent decades have targeted single buildings or individual building facilities. This includes the design of energy efficient buildings on the level of building envelope and constructions, energy systems and building services. While single building-level modelling has demonstrated numerous technical and economic benefits, it is vital to scale up the approach and consider the larger picture of cluster of buildings, districts, and cities. Nowadays, cities and districts are becoming more and more interconnected in terms of energy supply systems, and the transition towards smart connected thermal and electrical grids is inevitable but also has multiple benefits on both demand-side and supply-side levels (Dakheel A., 2020). With such large-scale evolvement of smart and flexible grids, there is an urgent need to move from analysing the performance of single buildings and upscaling the efforts to integrated building clusters and interconnected energy efficient and flexible cities and neighbourhoods. There is currently a scarcity of validated procedures and standards when it comes to modelling large scale building clusters, devoted to district or city level, which affects the overall results accuracy and consistency (Jepsen et al., 2020).

In the recent decades, legislations, theoretical investigations, and practical applications in Denmark have been concentrated on improving the design and operation of single buildings and facilities. This study aims at scaling up the efforts and deals with modelling, simulation, and improvement of the performance on a district/city level. A case study of an island district is considered aiming to establish and assess the first Danish positive energy district employing dynamic energy modelling. An open-source urban scale modelling tool is used, City Energy Analyst (CEA), where the district is modelled considering all specifications and characteristics of buildings and the corresponding energy supply systems. The base case scenario is simulated, and the performance is calibrated using actual data. Then, multiple energy improvement measures targeting the buildings envelope as well as the energy generation and supply systems are developed and simulated to assess the impact on the overall energy consumption for heating and electricity. Considering the results of the improvement measures, a number of improvement packages are designed, each having a collection of energy efficiency measures, and then integrated in CEA. The district performance under each scenario is simulated where the consumption is predicted and compared to the base case scenario. The case study island considered has ambitious aims to expand its renewable energy systems capacity and become fossil-fuel free in 2030. The study will provide preliminary results, forming a basis to aid energy system future retrofitting and upgrading in the district with the aim to establish the first PED in Denmark in compliance with the EU strategy.

CITY-LEVEL ENERGY MODELLING METHODOLOGY

In this work, the City Energy Analyst (CEA) urban modelling tool is employed and used to develop an interconnected district-level energy model and investigate various energy improvement measures and scenarios aiming to enhance the overall energy performance. In this section, a short presentation of the CEA tool is provided, highlighting the methodology for modelling, simulation and prediction.

CITY ENERGY ANALYST FOR URBAN MODELLING

As stated in the introduction, a massive amount of research and investigations dealing with single buildings and their performance improvement have been reported and analysed, but there is a scarcity when it comes to tools targeting energy performance modelling and assessment on the level of streets, districts, or cities. One of the emerging tools for urban-scale modelling and analysis is the City Energy Analyst (CEA). CEA is a free open-source tool for analysis & optimisation of urban energy systems (The A/S group – ETH Zurich). It was developed and released in 2017 by the ETH Zurich in Switzerland (The A/S Group – ETH Zurich). The CEA tool employs a white box modelling approach where all area/district details are included as inputs providing large flexibility in terms of modelling and scenarios design. In terms of interface, CEA has seven databases and six calculation modules combined within a user-friendly interface for design and operation inputs and a comprehensive results presentation section. Overall, CEA's integrated modelling and simulation platform with the supporting databases and calculation modules has major advantages and large capabilities in the field of urban scale modelling. This includes mainly the detailed and comprehensive modelling approach, possibilities for multiple scenarios design and simulations and user-friendly interface and detailed results presentation platform.

With its flexible modelling and design approach, CEA covers many applications for demand prediction, energy system analysis and optimisation in one combined platform. Even though the program is based on Python scripting, the developed interface and results dashboard ensure an easy usage and understanding. In general, the tool is divided into four parts:

- Input Data
- Database
- Tools
- Output Data

When a new project is initiated, the database and several inputs such as zone, district, terrain or weather must be chosen as these are important for the geospatial data initiation and calling. The program offers a limited selection of weather files for Switzerland and Singapore, while user files can be inputted in epw format. Afterwards, a map is opened which offers the possibility to select/choose the district to be investigated. Using built-in identification tools, CEA can automatically identify buildings in this area, which then are ready to be edited. The following characteristics can thus be changed and upgraded:

- Zone
  - Name, hight, floors
- Typology
  - Year, Usage-distribution
- Air-conditioning System
  - Type of HVAC, water supply
- Internal Loads
  - Occupancy density, loads
- Indoor Comfort
  - Temperature setpoint, humidity
- Architecture
  - Construction Types of walls, floors, windows, etc.
- Supply Systems
  - Type of cooling, hot water, electricity, heat supply
- Surroundings
  - Neighbouring buildings
- Schedules
  - Occupancy, appliances, lighting, water, heating, etc.

When all data are set, CEA calls several corresponding functions, also called tools that are the base of the analysis. Using such functions, the results regarding demand forecasting, radiation, LCA, energy potentials, network layouts or others are calculated. Hereby, it should be started with the "Archetypes System", whereafter it is possible to run the other tools. When a tool cannot be run, a solution-hint is given to the user. In the Output Section, the results can be seen in integrated interactive dashboards. There is a wide range of outputs and predictions including energy demand bars, indoor comfort maps and economic analysis and evaluation trends. A more detailed overview of the CEA modelling and design methodology can be seen in ***Figure 1***.

THE CASE STUDY

In this work, a case study of a district in a Danish island is chosen as a basis for modelling, simulation and energy performance improvement investigations using CEA. The city of Rise was chosen, which is located in Southern Denmark on the island of Ærø, shown in ***Figure 2***.

Ærø is a small island located in the southern archipelago of Denmark, having a total area of 88 km^2 and around 6200 inhabitants. The island of Ærø has an ambitious goal to become the first CO_2 neutral and renewable energy self-sufficient Danish Island by 2025, as well as becoming a fossil-fuel free island by 2030 [28]. Currently, around 55% of the island's energy supply comes from solar, wind and biomass-driven systems. The island has six 2 MW wind turbines and PV systems are deployed on a large scale in the residential sector with a current capacity of around 1.35 MW. To satisfy the island heating demands, three major district heating plants are employed, fulfilling around 65% of the total island heat consumption.

With the ambitious energy and environmental aims of Ærø island, this work aims to investigate the capability of establishing part of the island as the first Danish positive energy district and assess various design scenarios and possibilities of upgrading/modifying the current scheme and composition of energy supply and distribution. The selected Rise district is supplied by the company "Rise Fjernvarme" to satisfy district heating needs for the majority of the houses and buildings. The district heating system produces around 2,250 MWh per year, where the production is divided equally between wood pellets and solar thermal heat (Rise Fjernvarme, 2019). The next sections will highlight and describe the process of modelling, analysis and enhancement of the energy system design in Rise using the CEA tool methodology described earlier.

INPUT DATA DESCRIPTION

To model and assess the Rise district energy performance, the corresponding characteristics and inputs needs to be established in the CEA tool. As mentioned earlier, the tool starts to map the area and determine the buildings located in the chosen district. Then, the number of floors and shadowing from neighbouring buildings can be adjusted and integrated. ***Figures 3*** and ***4*** show a close-up of the map area as modelled in CEA with 3D models of the buildings considered.

Although CEA provides valuable benefits and capabilities in terms of the flexible energy modelling approach and the user-friendly interface, the tool has also some drawbacks which need to be addressed manually by the modeller. This includes some limitations in the automated reading and modelling of the buildings in the selected area. Some issues were encountered including the failure in automatically reading the number of floors

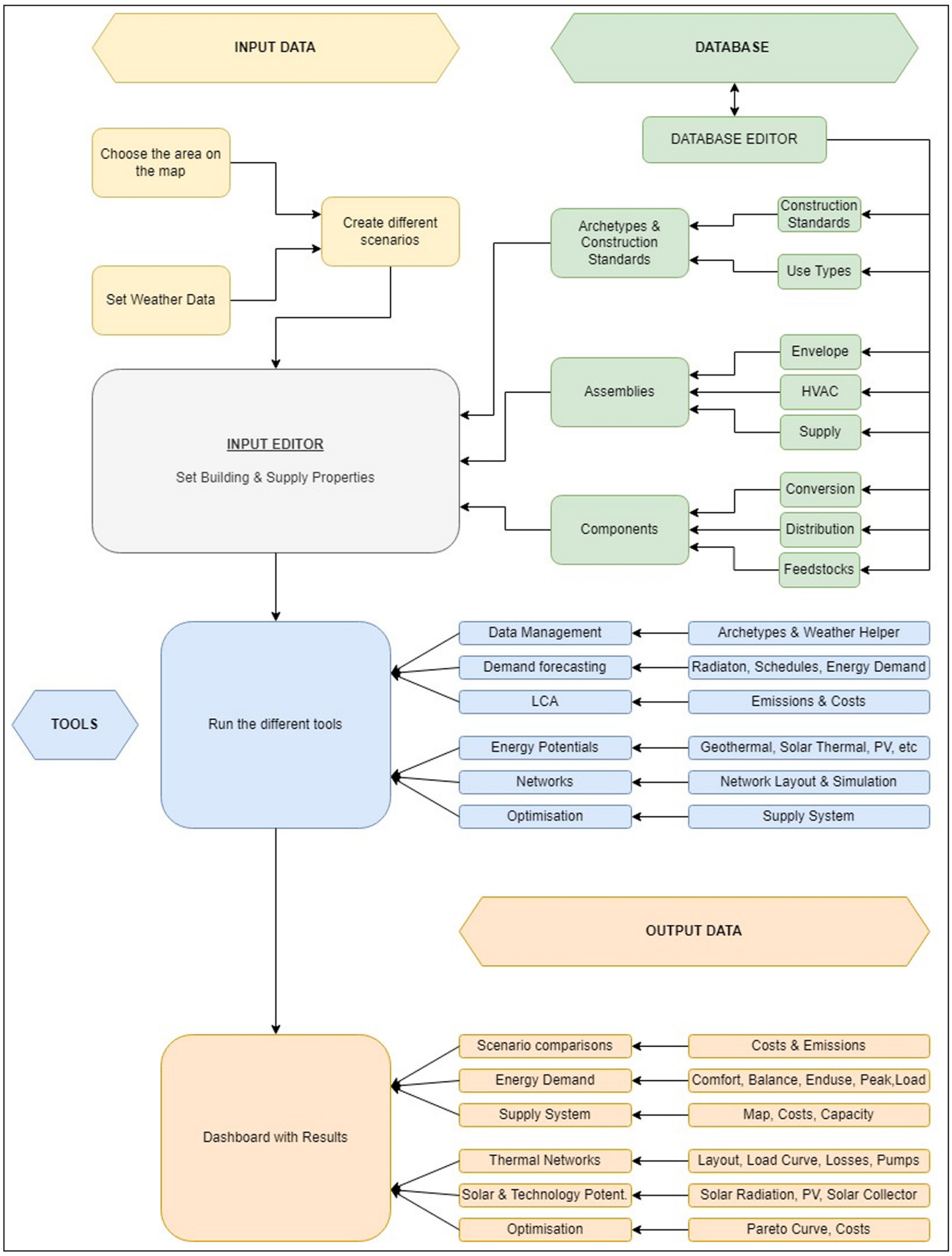

Figure 1 CEA Modelling and Assessment Methodology.

Figure 2 Rise location on Ærø island.

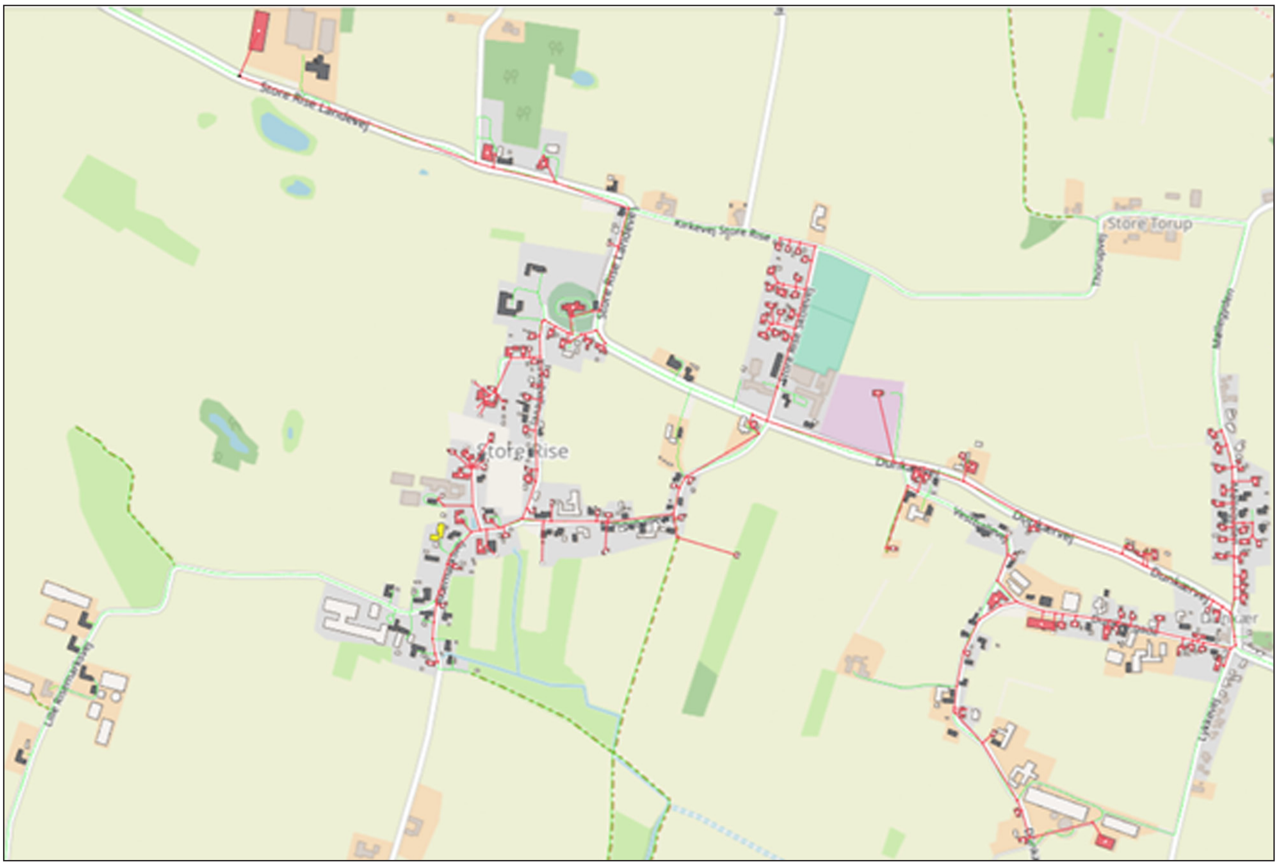

Figure 3 The modelled area in CEA, the city of Rise.

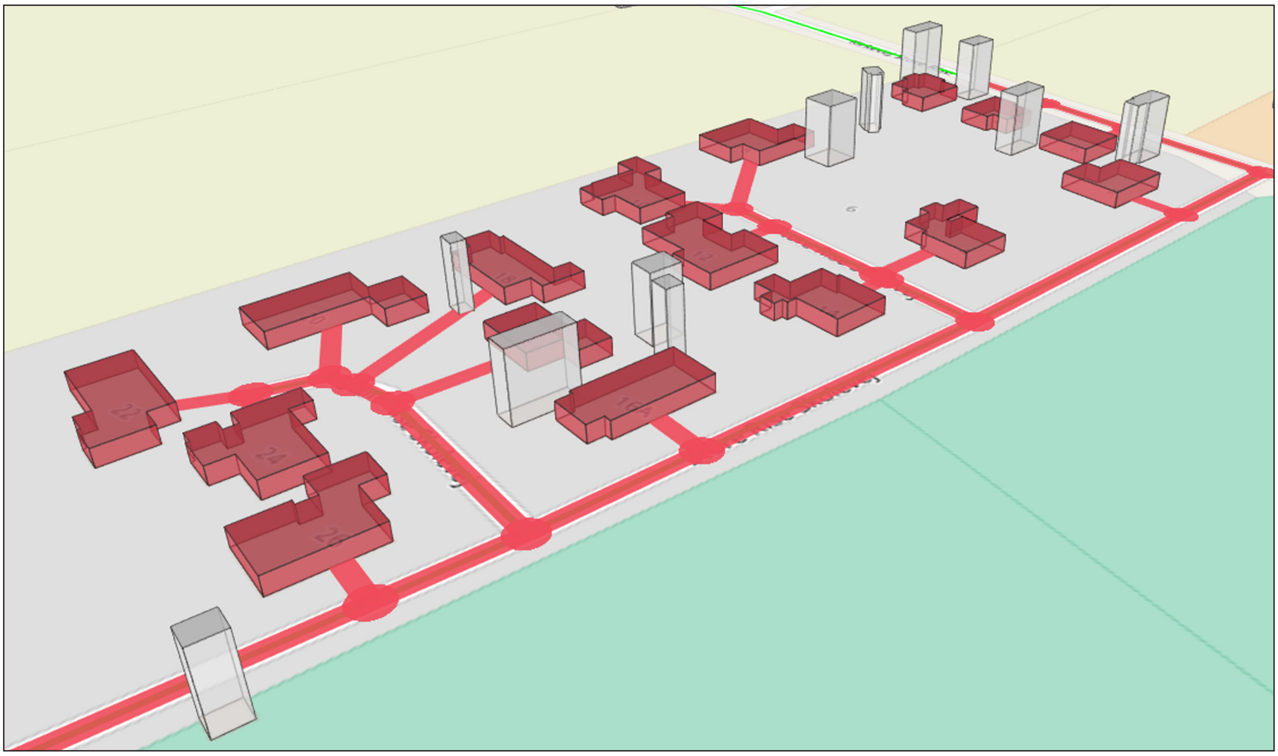

Figure 4 One street example in Rise, shown in CEA.

for each building and building orientation. In addition, other objects such as sheds, bins and empty boxes were read as buildings. Regarding garages or canopies, which are often located directly next to the house, the problem is that they are seen as part of the building and therefore living areas which increases the conditioned area that must be heated. Thus, the Danish Building and Housing Register (BBR) data (Bygnings- og Boligregistret, 2018), which includes detailed specifications on all Danish buildings, was used to manually correct the flaws and upgrade the building models in CEA.

A preliminary analysis was made to show the importance of such manually implemented alterations. ***Table 1*** compares the real-life consumption of electricity, with the baseline scenario with and without the alterations. It is shown that the electricity predictions gap decreases from 25% to only 6% when the issues of geometry are solved including the elimination of faulty read building areas.

The CEA tool needs weather data as an input to determine and evaluate the energy performance of the buildings in the selected district. As there are not readily default weather data available for the island of Ærø, data for the island of Tåsinge were used (Climate One Building, u.d.). The distance between these two islands is only 20 kilometres. In the weather file, the temperature data were updated to original data from Ærø, while all other data remained on Tåsinge data (ÆRØ, 2020). Thus, the assumption of weather conditions has a little impact on the area energy analysis.

MODELLING RISE DISTRICT IN THE CEA-TOOL

As the geometrical information of the buildings are updated and the weather conditions are established in CEA, the rest of the information regarding the Rise district needs to be introduced in the tool to compete the model. Obviously, the more inputs and details introduced, the more accurate the model will be. These include:

- Typology
- Architecture/envelope
- Internal loads & indoor comfort
- Schedules
- Supply Systems

The inputs for these categories are explained in the following sections.

Envelope

The envelope measures are categorised by their building performance year (BPY), and all the construction standards are according to the Danish building regulations (Bolig- og Planstyrelsen, u.d.). A BPY is defined based upon the last renovation year, so if there is no renovation done on the building, then the building construction year is the BPY. An overview of the used thermal transmittance (U-values) for the different categories is shown in ***Table 2***, all the units for the thermal transmittance is given in [W/m²K]. As shown, the buildings are categorized into six main categories, considering the year of construction, last renovated. This starts with buildings dated back before 1920 to newly built or retrofitted buildings in 2020.

Typology, Internal loads, Schedules & Indoor Comfort

The internal loads, schedules and indoor comfort are related to the building typology. In this case study there are five different typologies, and these are industry, museums, offices, retail, schools, and single residents. The specifications for the different typologies can be seen in ***Table 3***.

Supply Systems and HVAC

The heating supply system of Rise is majorly divided upon the three largest categories from ***Figure 5***, which will be explained in the following section. ***Table 4*** describes the simplified distribution.

The HVAC system in Rise consists of heating, ventilation, and hot water subsystems, while the cooling is neglected and there are no controllers incorporated. An overview of the HVAC system can be seen in ***Table 5***.

	WITHOUT GEOMETRY ALTERATIONS		WITH GEOMETRY ALTERATIONS	
REAL ELECTRICITY CONSUMPTION [MWH/YR]	ELECTRICITY CONSUMPTION [MWH/YR]	DIFFERENCE WITH RESPECT TO REAL DATA [%]	ELECTRICITY CONSUMPTION [MWH/YR]	DIFFERENCE WITH RESPECT TO REAL DATA [%]
3408	4531	25	3624	6

Table 1 Comparison between the real consumption and the baseline scenario both with & without the alterations in building geometry.

STANDARDS	BPY	WINDOWS	ROOF	WALL_IN	WALL_OUT	BASE
Standard 1	<1920's	3.5	0.5	0.7	1	0.6
Standard 2	1920 to 1960's	3	0.47	0.65	1	0.5
Standard 3	1961's to 1981's	2.9	0.45	0.6	1	0.45
Standard 4	1982's to 2005's	2.9	0.2	0.3	0.4	0.3
Standard 5	2005's to 2010's	1.8	0.15	0.2	0.3	0.2
Standard 6	2015's to 2020's	1.5	0.15	0.2	0.2	0.2

Table 2 Various buildings categories with their corresponding thermal transmittance in W/m²K.

BUILDING TYPOLOGY	MAX OCCUPANCY [M²/PERSON]	LIGHTING LOAD [W/M²]	APPLIANCE LOAD [W/M²]	HEATING SETPOINT [°C]	HEATING SETBACK [°C]
Industrial	15	15	10	19	15
Museums	3	10.8	7	21	15
Offices	14	10	7	20	17
Retail	8	20	4	20	17
Schools	3	10	4	21	17
Single houses	10	10	8	21	18

Table 3 Specifications for the different typologies.

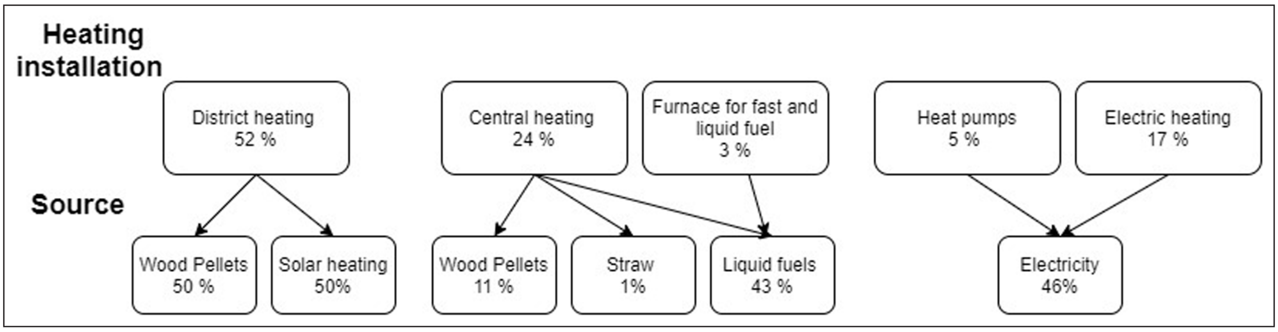

Figure 5 Different heating installation and sources provided by the BBR register.

DISTRIBUTION	PERCENTAGE
Covered by district heating	71
Central heating by oil	13
Heated by electrical heaters	16

Table 4 Overview of the simplified energy supply system distribution.

STANDARDS	BPY	HEATING	HOT WATER	VENTILATION
Standard 1	<1920's	Radiator (90/70)	Medium temperature water (45/10)	Window ventilation
Standard 2	1920 to 1960's	Radiator (90/70)	Medium temperature water (45/10)	Window ventilation
Standard 3	1961's to 1981's	Radiator (90/70)	Medium temperature water (45/10)	Window ventilation
Standard 4	1982's to 2005's	Radiator (70/55)	Medium temperature water (45/10)	Window ventilation
Standard 5	2005's to 2010's	Floor heating (40/35)	Medium temperature water (45/10)	Mechanical ventilation with demand control
Standard 6	2015's to 2020's	Floor heating (40/35)	Medium temperature water (45/10)	Mechanical ventilation with demand control

Table 5 The HVAC settings for the different building standards.

THE BASELINE SCENARIO

According to information from the BBR, Rise Fjernvarme, and consumption data from Ærø, 238 buildings have a heating demand in this area, and out of these approximately 123 are supplied by the district heating company (Rise Fjernvarme, 2019) (ÆRØ, 2020) (Bygnings- og Boligregistret, 2018).

The approximate heating distribution and the energy sources can be seen in ***Figure 5***.

The historic consumption data indicates that the city consumes approximately 3,408 [MWh/year] electricity (ÆRØ, 2020), and the district heating company supplies approximately 3500 [MWh/year], to the 123 buildings which are connected to the district heating grid (Bygnings- og Boligregistret, 2018). The simulations in CEA consist of 211 buildings and are divided, as seen in ***Figure 3***, into two categories. The grey buildings on the map are supplied by central heating sources or electrical heating, and the red ones use district heating.

BASELINE SCENARIO ENERGY RESULTS

As a first step before moving to energy improvement measures implementation, the base case scenarios performance of the Rise district needs to be simulated and reported. On the holistic level, the baseline simulations have shown that the city consumes 8515 MWh of heat and around 3624 MWh electricity per year. In the following sections, these numbers will serve as the reference values to evaluate different measures and packages regarding energy improvements and renovations. ***Figure 6*** provides an overview about the utilisation of heat and electricity.

In addition to the overall energy consumption numbers for heating and electricity, CEA also simulates the indoor air comfort conditions, mainly temperatures and moisture content. ***Figure 7*** shows the comfort charts with indoor temperature and moisture levels for one of the residential buildings selected in Rise. It is evident that the building has an acceptable indoor comfort conditions on average, however with notable lower indoor temperatures in some periods of the year. This may be due to the generally lower indoor temperatures accepted in Danish buildings compared to other countries.

ENERGY IMPROVEMENT MEASURES

After simulating the base case scenario of the Rise district, multiple energy improvement measures and scenarios will be investigated in this section aiming to improve the overall energy performance of the district and reduce its energy consumption. Such measures will deal with both the building envelope and the energy systems design. For example, the district heating system is currently supplied by around 50% solar heating and 50% wood pellets, which makes it an interesting case to investigate how a decreasing heating consumption could lower the needed wood pellet capacity. In the following sections, different energy efficient measures and packages will be introduced to enhance energy efficiently and lower the consumption.

Envelope Measures

According to the BBR-data, the average building performance year for Rise is 1949, which means that the typical building is quite old and generally not very energy

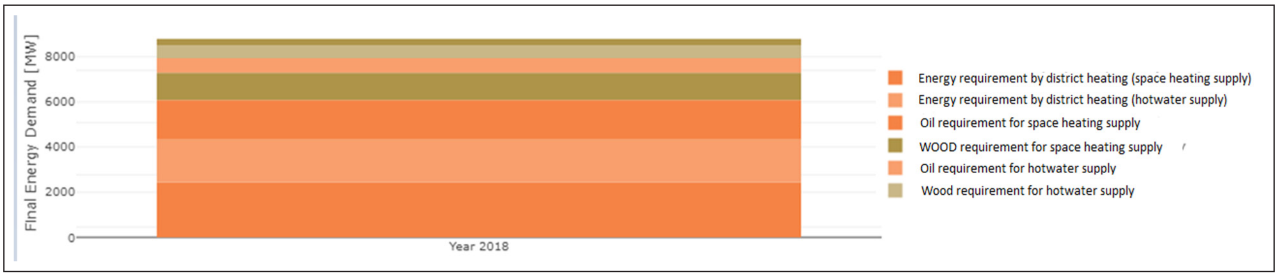

Figure 6 The heat consumption of the district with resources breakdown.

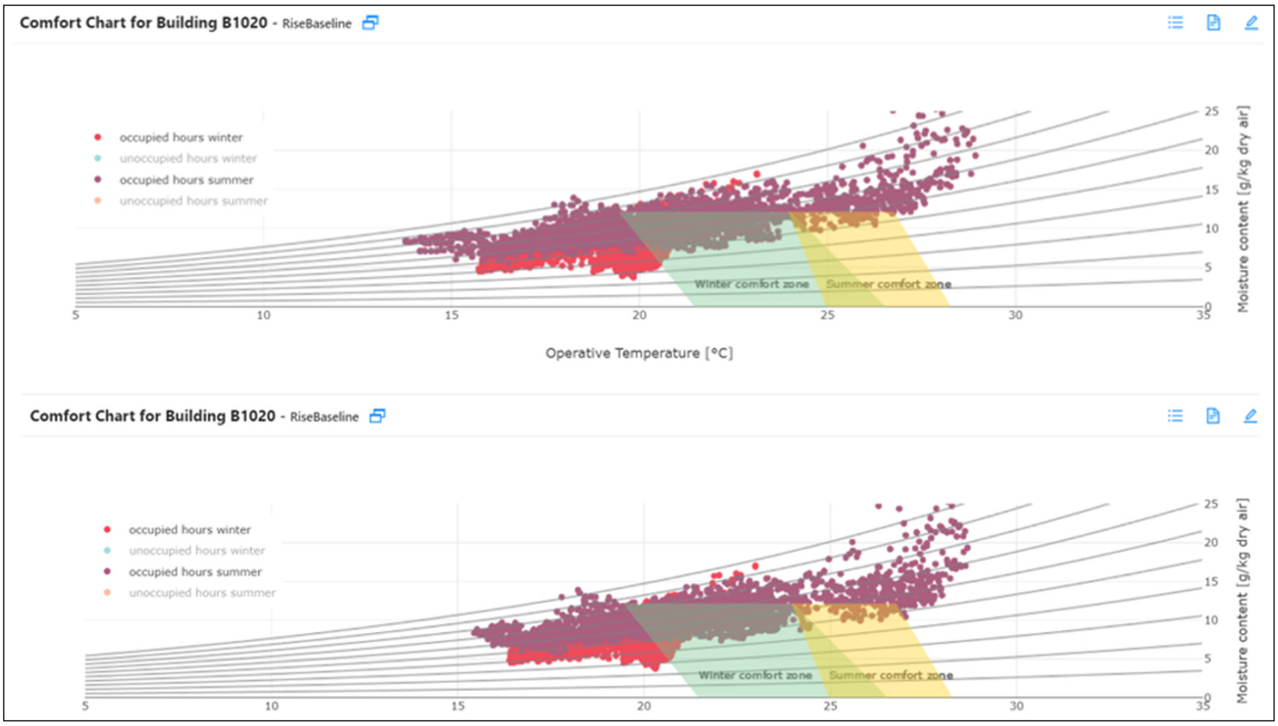

Figure 7 Comfort chart for the residential building B1020 in Rise with temperature and moisture levels.

efficient. Several measures were introduced regarding the envelope, including upgrading windows, walls, floors, and roofs. The standard values were changed in a way that they comply with the BR18-regulation (Bygnings- og Boligregistret, 2018), the latest Danish building regulation. Even though, the district heating company would not have that big of an influence on the inhabitants of these houses, but it is assumed that most of the houses would anyway undergo a renovation within the next decade. ***Table 6*** shows the upgraded values regarding the thermal transmittance in case of envelope enhancement measures.

Supply System Measures

While the building envelope improvements are vital for future energy efficient Rise district, the enhancement and upgrade of the current energy systems into energy efficient alternative units and renewable energy systems is key towards attaining energy and environmental goals of the island. Thus, another set of measures targeting the improvement of the energy supply systems were developed and assessed aiming to evaluate the impact on the building energy performance and the corresponding energy consumption profile. In terms of lighting, the lighting capacity for the baseline scenario ranges between 8 and 15 W/m^2, depending on the building typology. For the improved BR18 standards, this is set to be 5 W/m^2 which is assumed to be reached by installing LED lights. In the measure called "HP", heat pumps (HP) replace all the individual boilers using oil and wood in the district. This measure also ensures that the energy mix of Rise is primarily renewable where fossil fuels are phased out. Another measure called "100% DH" connects all the buildings to the local district heating, where no individual supply systems are allowed. Two other measures include increasing the capacity of PV/PVT to approx. 1 MW as part of the thermal and electrical grid. While both systems will feed the electricity supply to the island, the PVT system has the benefit of surplus heat production. ***Figure 8*** shows the electricity & heat production of the installations.

Energy Improvement Measure Results

The energy improvement measures listed above are implemented and simulated one by one in CEA and results regarding the overall electricity and heating savings compared to the baseline scenario are shown in ***Figure 9***. As highlighted by the results, the envelope measures can save up to 10% of the heating demand, with very minimal impact on the electricity levels. The lighting improvement measure on the other side saves up to 36% of the electricity consumption.

On the other hand, the energy supply system enhancement measures show very different results depending on the measure implemented. While the 100% district heating system measure allows minimal heating savings of only 3%, the PVT systems show promising results with reported heat savings up to 35% in addition to 46% reduction on electricity consumption. In addition, the heat pump measure can reduce the heat consumption by 24% but increases the electricity consumption by 27%. Hereby, the baseline scenario numbers should be taken into consideration, as heat consumption is more than twice the electricity consumption, providing a larger potential for saving. Therefore, measures allowing heating savings are highly favourable in this case from a technical perspective. Obviously, if an economic approach is implemented in comparing different measures, the electricity and hearing prices would determine he most optimal measures to select.

Energy Improvement Packages

In actual real case energy retrofit process, it is generally a collection or set of measures which are implemented in

	WINDOWS	OUTSIDE WALLS	INSIDE WALLS	FLOOR ON GROUND	INTERNAL FLOORS	ROOF
Thermal transmittance BR18 [W/m²K]	1.8	0.3	0.3	0.2	0.5	0.2

Table 6 Thermal transmittance values for the envelope measures.

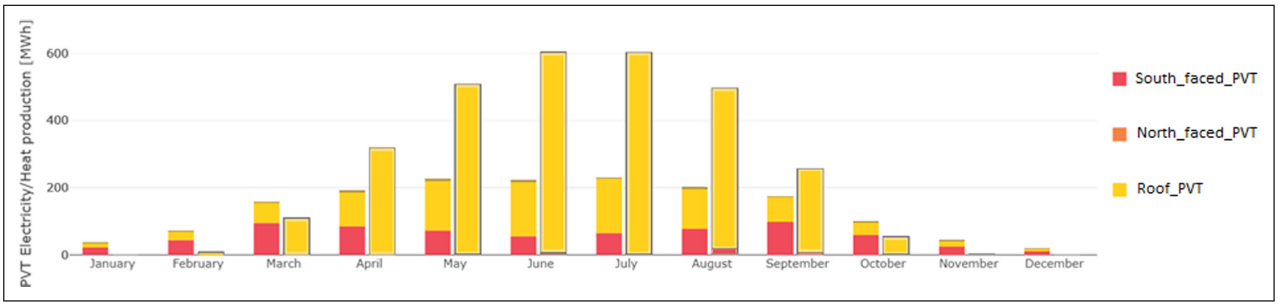

Figure 8 Overview of the PVT production, the left column in every month is the electricity [MWh] production and the right is heat production [MWh].

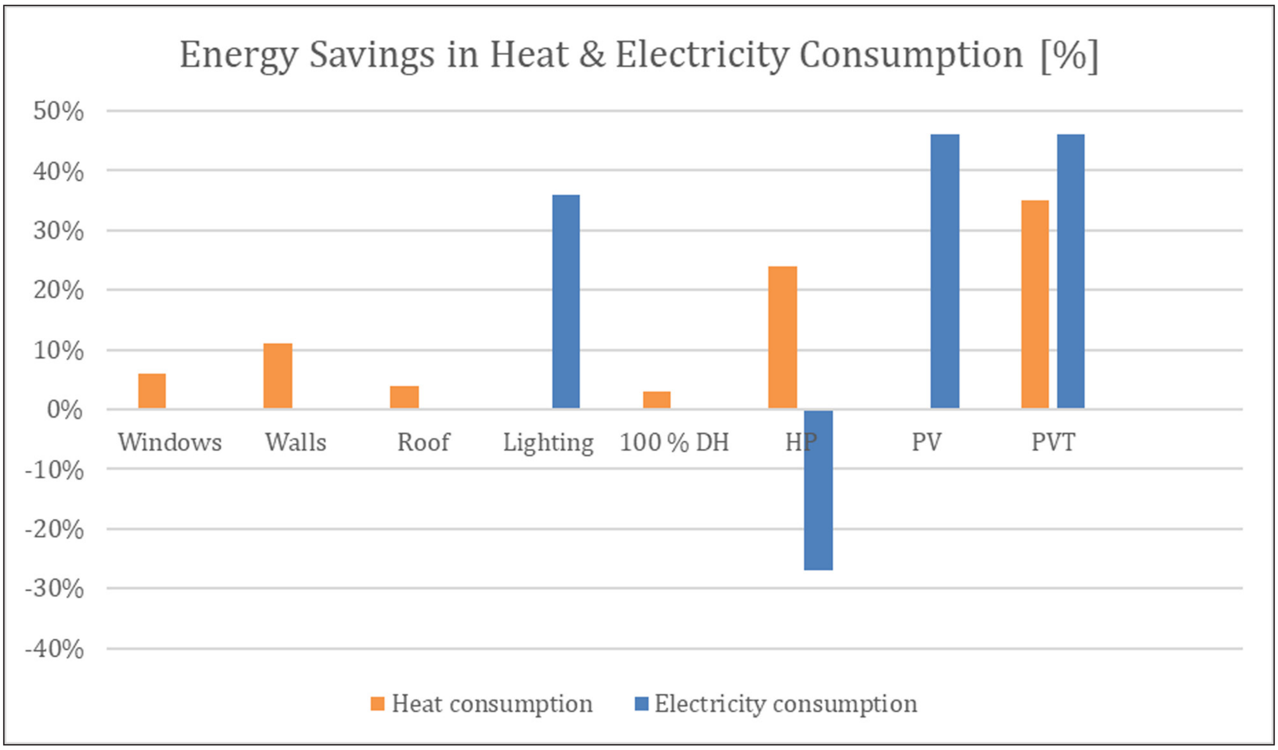

Figure 9 Energy savings in Heat & Electricity consumption compared with the Baseline Scenario.

	PACKAGE 1	PACKAGE 2	PACKAGE 3	PACKAGE 4	PACKAGE 5	PACKAGE 6
Windows	■	■	■	■	■	■
Walls	■	■	■	■	■	■
ROOF	■	■	■	■	■	■
Floor Base	■	■	■	■	■	■
Lights	■	■	■	■	■	■
HP		■		■		■
PV			■		■	
PVT				■		■
100 % DH					■	
Wind Turbine						■

Table 7 Overview of the different packages and corresponding measures.

a certain district rather than only one measure at a time. Due to the dynamic nature of the measures, dynamic energy simulation tools as CEA are valuable in this regard to estimate and predict the impact of implementing a group of measures at once. After simulating the impact of each measure alone, the different measures are collected in several energy improvement packages to determine the impact on the building energy performance. The packages were designed in a way that all of them include the envelope changes, but the supply system changes included were varied. ***Table 7*** gives an overview of the packages and their corresponding measures.

To investigate if Rise could become a positive energy district (PED), it was decided to investigate which measures and energy sources have an impact on the overall performance of the city.

Package 1 is chosen to investigate how energy renovations could affect the total energy demand of the different buildings. It only includes all improvements dealing with the envelope. Packages 2, 3 and 4, are all related to envelope improvements and then adding an alternate heating source, with the following composition:

- Package 2: Envelope + Heat Pump
- Package 3: Envelope + Photovoltaics
- Package 4: Envelope, HP + PVThermal

Package 5 connects all the buildings to the existing district heating system, while Package 6 aims at adding renewable energy systems sufficient to establish a Positive Energy District.

- Package 5: Envelope + 100% DH
- Package 6: PED (Envelope, HP, PVT's and Wind turbines)

When investigating the possibility for a PED establishment, Package 6 is built upon Package 4, which is the package closest to the target, as it produces more heat than is required by the district. To establish a PED, it was then decided to install wind turbines in this scenario, where the needed capacity to fulfil the remaining electricity demand of about 2200 MWh was calculated as being 0.71 MW of wind power capacity. As the electricity is produced by both PV's and wind turbines, then it is assumed that on a city located on an Island, it would be feasible that one of the production units would be able to always deliver the necessary power. However, if this is not the case, then it would be relevant to investigate the possibility to install a battery or have grid connection as an option, as the grid of Ærø is primarily driven by carbon neutral production units (Kommune, u.d.).

Energy Packages Results

The six different energy improvement packages built are implemented, one by one, in the CEA tool and the performance of the Rise district was simulated and reported in terms of heating and electricity consumption. The results of each package implementation are compared to the base case scenario to assess the savings. ***Figure 10*** gives an overview of the heating and electricity consumption savings attained in the case of each package.

Package 1, where only the envelope improvement measures are considered along with lighting system upgrade, results in a heating consumption reduction of 17% and an electricity consumption reduction of around 35%. When different heating sources are added in the packages, the heating consumption is reduced in the case of all the packages, while the electricity consumption is only reduced for four out of the five other packages compared to Package 1. Package 2 with the heat pumps obviously increases the electricity consumption but was on the other side able to reduce the heating consumption by around 85%. As a summary, Package 4 showed the most promising results with a reduction in electricity consumption of 62% and a generation of extra heating exceeding the district need by 20%. Thus, this Package was used as a basis in establishing a Danish PED by including the possibility of integrating a wind turbine capacity. This has led to Package 6 saving 100% on the electricity consumption and generating excess heating as well. It is important to note here that the calculations carried out and reported are on yearly net energy level.

DISCUSSION

When reviewing the different packages along with their impact on both the island heating and electricity grids, Package 4 with the Envelope improvement, the installation of individual heat pumps and the combined PV and solar thermal units, has the highest influence on the heating demand. This package could be a great addition to the district heating network in Rise, as it could lower the need for district heating both in the

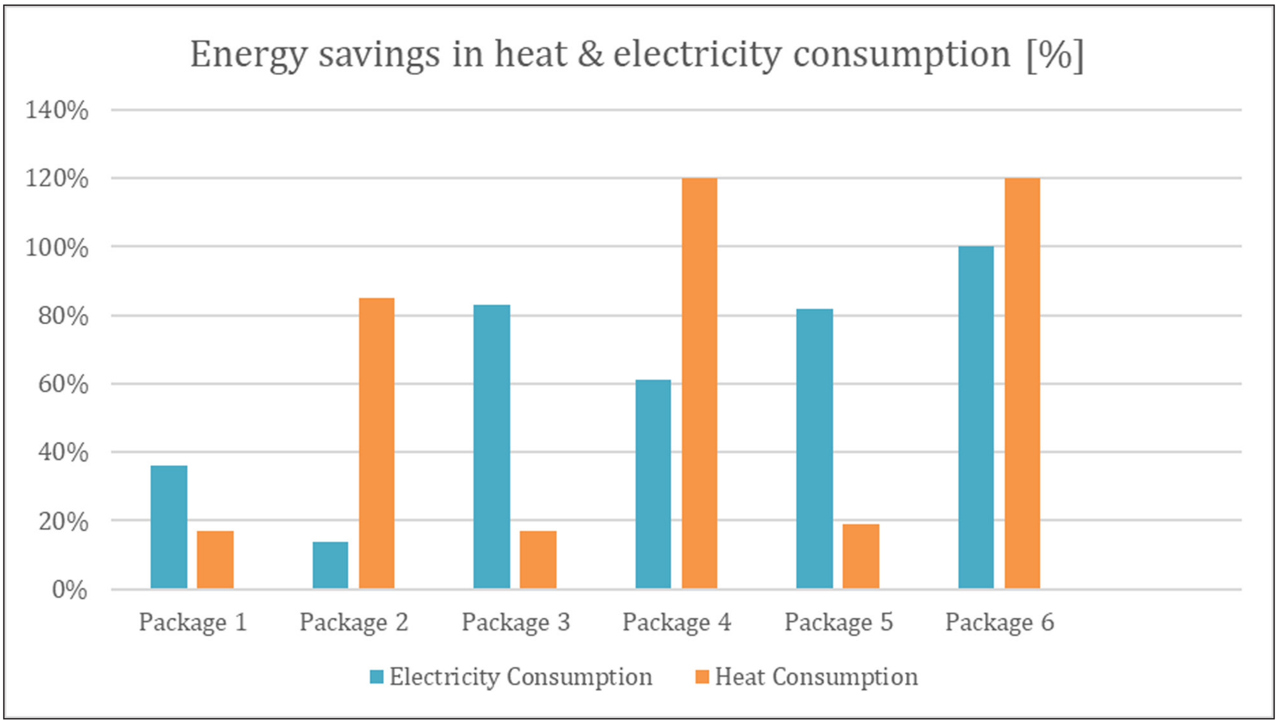

Figure 10 Energy savings in heat & electricity consumption compared to the baseline scenario.

summer months where the sun is available, and then it could also lower the demand in the winter months with the usage of the heat pumps. One of the original ideas was to investigate the establishment of a positive energy district in Rise. Based on the analysis carried out, such aim could not be realized without expanding the wind turbine capacity supplying the district. As an example, when installing the PV and PVT systems, it was decided to install these on all the available rooftops, allowing the reduction of 35% of the baseline heating demand and 46 % of the baseline electricity demand. Package 4 which includes PVT and a heat pump, gets close with improvements of 85% heating and 61 % electricity.

To establish a PED though, Package 6 was developed with the addition of 0,7 MW of wind power capacity. Since Ærø has already six 2 MW wind turbines, the proposed addition of wind turbine capacity doesn't seem out of reach (Ærø Kommune, 2021). This would transform Rise into a positive energy district and will be a step forward towards a fossil fuel-free Ærø, as all the energy is supplied by renewable sources such as wind, sun or biomass. On the other hand, the investigation carried out has several points which might be improved in future work. One extension to the analysis from a technical perspective would be the addition of battery storage system. This was not included due to limitations in the tool considered. However, a battery storage system would aid in balancing the supply and demand sides, especially that multiple renewable energy systems are employed. Another improvement which could be investigated in the future would be integrating more wind power capacity and lowering the PV unit's capacity employed. This could be part of a holistic analysis on the level of the whole island, rather than a small district as Rise. In addition, the investigation and assessment in this study didn't take the economic perspective into consideration, even though it has a big impact on the decision making when upgrading the systems and switching to alternative solutions. Thus, the impact of the measures in this study has been reported only employing a purely technical approach and considering the impact on heating and electricity consumption as indicators. On the other hand, while the economic feasibility and payback period of upgrading the envelope will not highlight this measure as a favourable measure, the demands by the Danish building regulations in terms of building envelope specifications is a major driver towards the envelope upgrade as part of regulations and standards compliance. As a summary, an overall techno-economic approach needs to be implemented to highlight the optimal measures for the energy scheme improvement in the district and to aid future decision-making. This approach should also consider the latest building regulations in Denmark as a key constraint and baseline.

CONCLUSION

The building sector worldwide has a major contribution in the overall energy consumption with at least 35% share in the total energy and a similar contribution in the corresponding greenhouse gas emissions. In light of the energy and environmental goals and ambitions in the majority of the countries, buildings and building blocks are thus considered as a key component in the national and international legislations and initiatives aiming to reduce the energy consumption and the corresponding emissions and achieve the energy efficiency and environmental goals. When it comes to energy consumption in buildings, Denmark is not an exception. In the recent years, efforts in Denmark have been devoted mainly towards enhancing the design and operation of single buildings and facilities throughout an expanding block of theoretical investigations, practical applications and strict standards and legislations. This work is one of the first initiatives towards scaling up such efforts from single buildings performance enhancement to design and performance evaluation of energy efficient and positive energy districts and cities. A case study of an island district is considered for investigation with the aim to improve the overall energy system design as well as the buildings performance as a basis to establish the first Danish positive energy district. City Energy Analyst (CEA), an urban scale modelling tool is employed, and the considered district is modelled including all specifications and characteristics. Then the base case scenario of the district is simulated and actual data on the heating and electricity consumption are used for model calibration.

The calibrated model is then used as a baseline and multiple energy improvement measures targeting buildings envelope as well as the energy generation and supply systems are developed and implemented in CEA to report the impact on the overall energy consumption for heating and electricity. Based on the investigated measures, six improvement packages with measures combinations were formed and simulated. It was shown that a PED can be established in the considered district through a holistic improvement energy package of envelope-targeting measures, energy systems upgrades and renewable energy systems expansion. The package is made up of envelope insulation, LED lights, heat pumps installation, PVT units and wind turbine capacity expansion. This will allow satisfying the electricity needs on an annual net level, while generating 20% more heat in excess. The case study island considered in this work has very ambitious energy and environmental goals, with a well-established network of renewable energy systems in place. The long-term goal in 2030 is to expand the renewable energy systems capacity to become fossil-fuel free. Thus, the findings of this study along with the various scenarios developed and tested will serve as a preliminary assessment and form a basis to aid future decision-making in retrofitting the energy system and upgrading the buildings envelope and services. A future follow-up investigation would be combining the technical approach employed in this study with an economic approach to investigate the economic feasibility of the scenarios developed and provide a better holistic picture on the added value. In addition, the study forms a basis for establishing the first PED in Denmark and is in line with the recent EU strategy aiming towards the deployment and replication of 100 Positive Energy Neighbourhoods in Europe by 2025.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

The authors contribution to the work is as follows:

- Barbara Kristin Holmsund Jepsen: Investigation, Formal Analysis, Resources, Software, Visualization, Writing Original Draft
- Tom Walther Haut: Investigation, Formal Analysis, Resources, Software, Visualization, Writing Original Draft
- Muhyiddine Jradi: Conceptualization, Methodology, Formal Analysis, Investigation, Writing Revised Draft, Supervision, Project Administration

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