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Towards positive energy islands – a Danish case study

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Towards positive energy islands – a Danish case study

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Abstract. The Danish island of "Ærø" has the ambition of becoming the first Danish island to be self-sufficient in renewable energy and CO_2 neutral by 2025, as well as fossil fuel free by 2030. This work investigates the feasibility of re-designing part of the island's energy system to become the first Danish positive energy island (PEI), evaluating various design scenarios and opportunities for improving and modifying the current energy supply and distribution scheme. The district is modelled considering all building specifications and characteristics and the energy supply systems using the urban scale modelling tool City Energy Analyst (CEA). A simulation of the base-case scenario is performed to calibrate the performance. Different energy improvement strategies targeting building envelopes and energy generation and supply systems are created and implemented in CEA. Six improvement packages are created and simulated. It is demonstrated that a PEI could be built in the district under consideration through a comprehensive energy improvement package of envelope-targeting techniques, energy system upgrades, and the expansion of renewable energy systems. The package includes LED lighting, heat pump installation, and photovoltaic-thermal units. This will enable meeting the annual net need for electricity while producing 20% excess heat.

1. Introduction

Dynamic energy modelling and simulation have been crucial in identifying the effects of increasing the energy efficiency of the building stock and documenting the added benefit on the economical, technical, social, and environmental levels [1,2]. An increasing number of studies published in the past few years focused on urban regions, districts, and cities' energy modelling, analysis, and performance optimization [3,4]. It was shown that accurate urban areas and building cluster models require many inputs dealing with building envelopes, energy systems, loads, schedules, and connected energy networks. In this regard, it was highlighted that the predictions are frequently not as accurate as those of single building models because it is difficult to schedule human behaviour, characterize the urban climate, and characterize the additional complexity of upscaling the case of a single building from a larger perspective. Overall, there are no established standard approaches for modelling huge building clusters because the modelling methodologies and frameworks of large-scale building areas and cities are still undeveloped and have many issues and challenges to tackle. A recent comprehensive study by Belda et al. [5] has identified the key challenges and limitations of energy modelling software in the assessment of PEDs using five case studies in Denmark, Netherlands, Spain, Italy, and Canada. Recently, a variety of building cluster and city energy modelling approaches have been developed and implemented, allowing the estimation of the energy consumption of building districts and cities on a small- to medium-scale basis [6]. These tools and techniques all estimate a large area's energy demand based on its buildings' characteristics and specifications, topography, surroundings, geography, energy networks, and climate.

With the goal of scaling up the efforts from a single building to a district with building clusters, the major contribution of this work is to support the creation of the first Danish positive energy district through dynamic energy modelling. The district is modelled while considering all building specifications and features, as well as the relevant energy supply systems, using the open-source urban scale modelling application City Energy Analyst (CEA) [7]. A simulation of the base-case scenario is used for calibration. The impact on the total amount of energy used for heating and electricity is then evaluated using a variety of energy improvement techniques and packages targeting the buildings' construction and physical envelopes, as well as energy delivery and supply systems. On this basis, recommendations for the district's upgrade and renovation in terms of buildings and energy networks and systems are provided and discussed as well as the major limitations and challenges in modelling such PEDs and the must-have inputs for successful and effective modelling of PEDs.

2. Case Study

With a total area of 88 km^2 and about 6200 residents, Ærø is a little island located in Denmark's southern chain of islands. The overarching objective of Ærø is to eliminate fossil fuels by 2030 and become the first Danish Island to be self-sufficient in renewable energy by 2025. Currently, solar, wind, and biomass-powered systems provide for more than 55% of the island's energy needs. In terms of capacity, the island has six 2 MW wind turbines, all of which produce more energy than the entire island needs over a year. The residential sector has a significant deployment of PV systems, with a capacity of around 1.35 MW at the present time. Ærø comprises three main district heating plants, which together provide over 65% of the island's overall heating demand. The three plants are run on renewable energy sources, with solar thermal collectors providing around 55% of the supply. The part of the island considered a case study in this work is provided with district heating by the firm "Rise Fjernvarme", where the production is roughly evenly split between solar thermal heat and wood pellets.

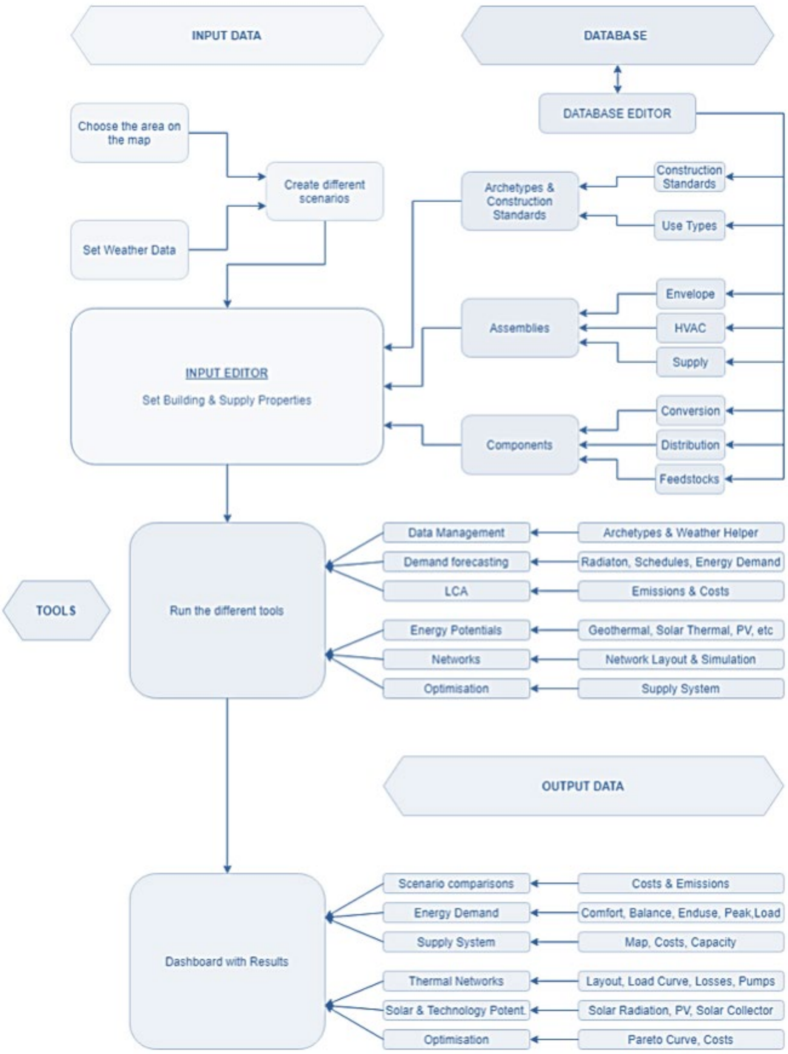

Figure 1. Overview of the CEA modelling and design framework

For modelling and simulating the island district's performance and operation, it was decided to use the CEA tool. Regarding the tool modelling and simulation framework, CEA possesses seven databases, six calculation modules, a user-friendly input interface, and a detailed results display interface. About half of Ærø island was modelled using CEA, and different scenarios were put into action and evaluated. Overall, the integrated modelling and simulation platform of CEA, along with the auxiliary databases and calculation modules, provides a wide range of capabilities and significant benefits for urban-scale modelling. This primarily consists of a thorough and precise modelling methodology, options for designing and simulating several scenarios, an intuitive interface, and an environment for presenting the findings in detail. Figure 1 depicts an expanded overview of the CEA modelling and design framework. The main input specifications include zone information, typology, energy systems, internal loads, indoor comfort data and setpoints, architectural details and construction materials, supply systems and building services, surroundings and neighbouring buildings, occupancy schedules, in addition to geospatial data. As all the required input data is introduced, CEA calls for the different built-in modules to perform calculations and services, including energy consumption forecasting, life cycle assessment, optimization, and data management. When the calculations and evaluations are completed, the CEA integrated interactive dashboard can be used to view the different results regarding energy, indoor comfort, economic assessment, and environmental evaluation.

3. Implementation Results

3.1. Baseline Case

The different characteristics specified in the previous section were collected and introduced in the CEA tool to simulate and evaluate the Rise district's energy performance. As previously mentioned, the tool begins by mapping the selected region and identifying the buildings situated in the designated district. The total number of storeys, along with the shading caused by nearby buildings, may then be modified and incorporated. Figures 2(a) and (b) show screenshots of the map of the area modelled in CEA and an image of one street, respectively. The different characteristics and specifications listed above have been collected and introduced in the CEA tool in order to simulate and evaluate the Rise district's energy performance. With the area and the corresponding weather conditions selected, the tool begins to map the region and identify buildings situated in the district. The total number of storeys along with the shading caused by nearby buildings may then be modified and incorporated.

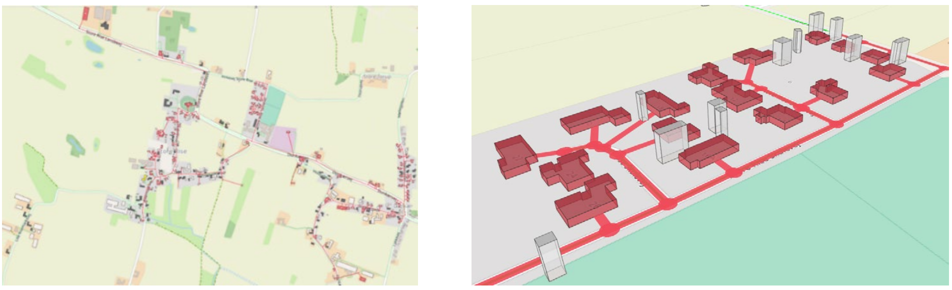

Figure 2. (a) map of the area modelled in CEA and (b) example of one street in the district

Furthermore, different building topologies, representing various building types and ages, were introduced to CEA, and the corresponding envelope specifications were added, including the construction year, the thermal transmittance coefficient, and window type. In addition, information on the internal loads, schedules, and occupancy patterns was defined, and information regarding the building systems setpoints and control patterns was added. In terms of the energy supply systems, the heating system is supplied by district heating, oil heating, and wood/pellets heating, with 71%, 16%, and 13%, respectively. Other active energy systems considered include ventilation, cooling, and hot water subsystems. As around 30% of the buildings in the district use individual heating systems, it is hard to get the actual consumption data to calibrate and validate the model. On the other hand, the

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overall electricity consumption of the area is reported by the electricity supply company. On this basis, the reported actual annual electricity consumption of the district is around 3408 MWh in 2020. The predicted consumption by the calibrated model was around 3624 MWh with around 6% deviation, which is deemed acceptable for a model of such a scale. For heating, the baseline simulation of the case study's performance over a year resulted in a total of 8515 MWh.

3.2. Improvement Measures and Packages

After modelling and simulating the Rise district's base-case scenario employing the calibrated holistic model in CEA, an array of energy-enhancement strategies and scenarios are examined with the goal of improving the district's overall energy performance and lowering its energy usage. The considered improvement actions deal with both the building construction and physical envelope as well as the design and architecture of the energy systems. Overall, the average building age in the district is around 75 years. This means that the buildings' physical envelope is a key component to target in order to attain energy and environmental goals. On this basis, three different energy-efficient actions are considered: (M1) exterior window upgrade, (M2) exterior wall insulation, and (M3) roof insulation. The desired end goal in terms of materials used and insulation thickness was considered to be the latest Danish building regulation BR18 [8] recommendations regarding existing building energy renovation actions. Furthermore, multiple energy-efficient measures were also considered to improve the design and operation of the energy production and supply systems. These include: (M4) upgrading the lighting system by installing common standard LED lights; (M5) replacing the individual oil and wood boilers in the district with heat pumps; (M6) expanding the district heating system to supply the whole district's heating needs; (M7) installing 1 MW of photovoltaic (PV) systems; and (M8) installing 1 MW of photovoltaic-thermal (PVT) systems. All of the considered measures aid the planned transition of the district towards phasing out fossil fuels and relying on renewable energy.

The eight listed measures were implemented and simulated one by one using the district model in CEA. The overall savings on the district electricity and heating consumption in each case are compared to the baseline district case, as shown in Figure 3. It is obvious that the majority of the measures lead to energy savings, in particular on heating consumption, with wall insulation saving 29%, roof insulation saving 26%, and PVT installation saving around 20%. In terms of electricity consumption, the upgrade to LED saves 36% and the installation of PVs saves 38%, while heat pump installation increases the need for electricity by 24%.

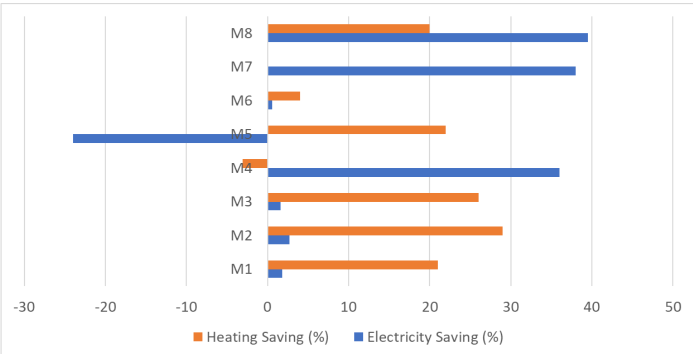

Figure 3. Impact of the energy measures on the heating and electricity consumption

Considering the results of the eight measures implemented in the district, six energy improvement packages were suggested to assess their impact on the overall energy performance of the district. Each package comprises two or more of the above-mentioned measures (M1 to M8). Table 1 shows the different packages with their corresponding energy measures. As highlighted in the table, all six packages include building envelope improvement measures (windows, walls, and roofs) in addition to LED light installation. It is also good to note that P6 includes the addition of 1 MW of PVT capacity as an additional renewable energy-driven power and heat source. The six developed energy improvement packages were introduced and implemented employing the district energy model developed in CEA.

Table 1. Energy improvement packages with different measures

	P1	P2	P3	P4	P5	P6
Upgrading Windows	■	■	■	■	■	■
Insulating Walls	■	■	■	■	■	■
Insulating Roofs	■	■	■	■	■	■
Installing LEDs	■	■	■	■	■	■
Installing Heat Pumps		■		■		■
Installing PVs			■		■	
Installing PVTs				■		■
District Heating Only					■	
Installing additional 1 MW PVTs						■

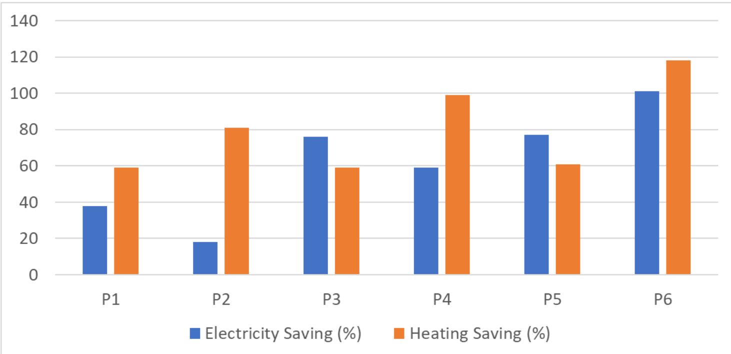

Figure 4. Impact of the energy packages on the heating and electricity consumption

The simulated annual savings on electricity and heating consumption of each package investigated are presented in Figure 4. It is shown that P1 allows for savings of around 58% on heating consumption and 38% on electricity consumption. In addition, while P3 allows 76% savings on electricity, P4 allows around 98% savings on heating consumption. Finally, P6 is a package demonstrating a positive energy island case, with an additional 1 MW capacity of PVTs, allowing covering the whole electricity needs and producing around 19% more heating than the annual demand.

4. Discussion and Conclusion

This work is among the first Danish initiatives to scale up efforts and actions from improving the performance of individual buildings to designing and evaluating the performance of positive and energy-efficient interconnected districts and cities. It was shown that a comprehensive energy improvement package, including envelope-targeting actions, energy system improvements, and renewable energy system expansion will enable meeting the yearly net electricity demands while producing 20% more heat than required.

While this work has demonstrated the potential of using white box modelling tools, in this case CEA, to model, design, and evaluate the performance of positive energy districts, the following limitations and challenges related to modelling such applications are highlighted: First, as the object is generally a large, complex area with multiple energy systems and networks and various building types and applications, data collection and integration are key hurdles. In this regard, obtaining accurate and sufficient data is time- and resource-consuming. For example, the area considered in this study includes buildings that use different types of heating systems. While it was relatively easy to collect data from the district heating company in terms of consumption, it was harder and sometimes not possible to get data from houses and buildings using single or individual types of heating, such as wood or oil burners. This problem could be even bigger in areas where collective systems and networks are not implemented. Second, obtaining an accurate geometrical representation of the buildings considered within the district is another challenge. In this regard, CEA was not always able to automatically read the number of floors in each building while being able to capture only the shape of the outer envelope and the orientation. Another issue is that the tool treats every object in the area as a conditioned building. This includes bins, storage boxes, and sheds. This issue has to be corrected and addressed manually. Third, while PEDs are primarily concerned with the energy systems and networks supporting the area, building envelope data is of high importance. For example, an area with buildings dating back to the 1920s will behave differently than an area with relatively younger buildings from the 2000s. In the case of CEA, building envelope information for Denmark was missing, and this had to be introduced and set up in the tool prior to the simulation and evaluation.

In addition to the limitations listed above, some of the must-have inputs for modelling PEDs have been identified throughout the work carried out in this paper. First of all, as PED renewable energy systems are intermittent in nature along with the dynamic operation of storage units, it is very important to include accurate inputs on the loads in the area, including electrical loads, heating loads, domestic hot water, and cooling and ventilation demands. Another important input for a successful PED implementation and modelling application is accurate and detailed models of the supply side of renewable and alternative energy systems. In the case of CEA, the tool has sophisticated PV, PVT, biomass heating, and sensible energy storage models but lacks some other technologies that are crucial for the Danish case, for example, hydrogen technologies and wind turbines. This has to be defined manually in the tool interface. Again, because of the intermittency and dynamic nature of the specific renewable energy systems in PEDs, data granularity and temporal resolution are of great importance. The data needs to be available at a very low level, preferably building and facility level, but also on an hourly or even subhourly resolution. This has been dealt with in regard to the CEA tool used in this study. Finally, an indispensable requirement when modelling and designing PEDs is having a proper and effective optimization framework with superior decision-making capabilities. This is not limited to designing a district with a surplus of energy generation but also includes different criteria to be satisfied related to thermal comfort, CO2 emissions, renewability of supply, and economic impacts. This is a major gap in regard to using the CEA tool in this study, as the scenario selection and evaluation have to be implemented separately and compared individually.

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