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A Research Agenda

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Buildings interaction with Urban Energy Systems – A Research Agenda

Summary

The goal towards a fossil free energy system is expressed in amongst others European and national targets, and puts pressure on the application of renewable energy sources combined with energy efficiency. Many cities are even more ambitious than their national targets and want to be among the first to demonstrate that they can become not only smart fossil-free energy cities but sustainable in a wider sense, including water, waste, transportation and more. In the current paper, the research agenda to support such goals through smart city efforts is presented for a few European cases as examples, focusing on the impacts that buildings play in the overall energy system. Here buildings are not only consumers but rather prosumers that are able to produce renewable energy themselves. Buildings moreover offer potential storage capacities that can be utilized in demand shifting, which is necessary to enable increased penetration of renewable energy in the energy grids.

Introduction

The goal towards a fossil free energy system is expressed in amongst others European, Danish and Norwegian targets , and puts pressure on the application of renewable energy sources combined with energy conservation, efficiency and storage (Commission, 2010), (European Energy Research Alliance, n.d.), (The Danish government, 2011). The goal is not limited to the energy use, but the overall impact of cities (European Commission, 2013), (Cities, n.d.). Many cities are even more ambitious than their national targets and want to be among the first to demonstrate that they can become smart fossil-free energy cities (Zero, 2007).

Making the building stock energy-efficient enough to be operated only by renewable energy is a vital element in the realization of this ambition. Traditionally, energy-efficient building operation is handled at building level through building design, materials and facades, building energy management systems and user interaction. However, in the past few years more emphasis has been directed towards energy-efficiency and energy-producing measures for groups of buildings, or building stocks at neighbourhood and urban scales. As a consequence, buildings and their users are changing their status in the overall energy system perspective from consumers to prosumers, i.e. being consumers as well as producers of renewable energy in the form of electricity (PV and wind) or/and heat by solar thermal.

The increased penetration of fluctuating renewable energy sources into the energy mix puts a dramatic pressure on the task of stabilizing the electrical grid. Smart Grids were proposed as the solution to this challenge, i.e. handling the mismatch by using technological solutions for demand side management of electrical sinks. However, this seems not to be realistic any more as a stand-alone solution and there is therefore a search for additional solutions to stabilize the mismatch between energy production and demand in the future CO₂ neutral energy system. Here the question arises: Can a more proactive building energy management help stabilize the overall energy system?

The European research community has accepted the challenge to create better energy flexibility through optimised interaction between the building stock and smart grids. Examples of these new interdisciplinary research agendas will be analysed below. The authors acknowledge that there are many more projects on smart cities, on smart grid, smart buildings that are not referred here. In short, the following research will be presented:

The Joint Program on Smart Cities within the European Energy Research Alliance (EERA JP Smart Cities), (EERA, n.d.), provides a framework for this international research on enhanced energy efficiency and the large-scale integration of renewable energies, enabled through smart energy management at a city level. This collaborative approach is anticipated to provide added value for Europe.

The European research project READY, (EU READY, 2014) is a cooperation between Danish, Swedish and Lithuanian partners. The aim is to demonstrate solutions for large-scale low-energy building renovation across energy carriers, electricity and district heating. Special attention is given to the trade-off in investments in energy savings, renewable energy production, and demand-side flexibility technologies.

European demonstration project ZenN Near Zero Energy Neighbourhoods, (ZenN, 2014), aims to demonstrate approaches for large-scale energy-efficiency renovation of domestic buildings, emphasizing technical as well as non-technical aspects (the latter include amongst others architectural quality and cultural heritage, stakeholder engagement, socio-economic and governance dimensions). Running from 2013 to 2017, ZenN features renovation demonstration projects in Norway, Sweden, Spain and France.

The Danish strategic research Centre, CITIES, (Madsen, Heller, & Hermann, n.d.), is an international cooperation with 40 partners from academia, private and public organization and cities, that will address all aspects of the energy system, including gas, power, district heating/cooling and biomass, and most importantly methods to forecast, control and optimize their interactions through the use of advanced ICT solutions.

The Norwegian Research Centre on Zero Emission Buildings (ZEB) aims to “eliminate the greenhouse gas emissions caused by buildings” by developing “competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition”. The ZEB Centre includes a set of 11 pilot projects across Norway and runs from 2010 to 2017 (SINTEF, n.d.). A new centre application for the neighbourhood scale is currently under development, aiming to decarbonize the building stock in connection with energy and mobility infrastructures.

Finally, the Danish research and demonstration project EnergyLab Nordhavn that aims at demonstrating a full-scale holistic energy solution for the current phase involves renovation and new developments. The project runs from 2015-2019.

The European perspective

The European Commission has adopted a framework strategy for a resilient Energy Union in which energy efficiency is to be regarded as an energy source “in its own right so that it can compete on equal terms with generation capacity” (European Commission, 2015). The Strategic Energy Technology (SET) Plan Integrated Roadmap ((European Energy Research Alliance, n.d.), pages 1-3) identifies a “process of profound transformation” towards a more flexible and holistic European energy system with empowered citizens, better efficiency in buildings, infrastructures and the entire value chain, and more renewable and decentralised generation, optimised on a local/urban level.

Acknowledging that cities are foci of this transformation, the European Innovation Platform for Smart Cities and Communities was established to nurture cooperation between key actors from cities, industry, research and education, materialised in the Strategic and Operational Implementation Plans (European Innovation Partnership, 2013). With *Sustainable Districts and Built Environment* as one of three vertical pillars, *integration* and *interoperability* are emphasised as key challenges – in planning, design and management, in modelling and other decision-support, and in smart technologies that provide better control over demand responses – for the empowerment of citizens in their daily life. Also the Energy Efficiency in Building Alliance (E2BA) aims to develop “smart systemic approaches for green buildings and districts”, with the objective to demonstrate by 2020 at least 20 new technologies for “interactive sustainable buildings for energy neutrality/positivity in a block of buildings, for a further 15% reduction at district and city scale in energy and emissions by 2020” ((E2BA, 2013), p.20).

European Research Alliance

The European Energy Research Alliance (EERA), (EERA, n.d.) is a joint effort of leading European research institutes to develop new energy technologies for a low-carbon Europe. EERA coordinates and streamlines research and development activities, both national and European, and identifies synergies by coupling resources thus optimising pan-European energy research capabilities and infrastructures. EERA implements joint research programmes that support the SET Plan priorities (European Energy Research Alliance, n.d.).

Within the EERA Joint Programmes (JP) researchers establish strategic, permanent collaborations between European research organisations and institutes to form a virtual centre of excellence. The JPs shall address Europe's energy future by focusing research on energy technologies like photovoltaics and wind energy, but also infrastructure topics like smart grids, smart buildings and smart cities. Currently almost 3000 researchers from over 150 public research centres and universities participate in the different Joint Programmes.

Urbanisation is a growing trend that gives cities strong leverage towards energy efficiency - almost two thirds of global energy is consumed in urban environments. Smart cities use innovative technology and integrated approaches to provide high energy efficiency, sustainability and quality of life. They therefore play a prominent part in the European Strategic Energy Technology (SET) Plan as the building blocks for low-carbon energy systems.

JP Smart Cities (EERA-SC, n.d.) works on providing an integrated systems view as well as innovative, intelligent approaches to the design and operation of urban energy systems. Researchers aim to develop new scientific methods, concepts and tools designed to support European cities in their transformation into smart cities, focussing on large-scale integration of renewable energies and enhanced energy efficiency, enabled through smart energy management at the city level. The research questions involved in transforming cities into Smart cities are highly complex and can only be solved by taking an interdisciplinary, transnational approach.

The Joint Programme on Smart Cities consists of four sub-programmes:

- 1) **Energy in Cities** takes an integrated approach towards urban energy planning and transformation processes. It uses a unique integrated approach to merge urban and energy planning. The scientific tools to be developed will support cities throughout the transition process towards a low-carbon energy system – from systems analysis, vision development and pathway exploration to experimenting, assessment and implementation. The sub-programme will provide best practice examples of smart city visions for others to emulate. Similar work is done under (IEA EBC Annex 67, 2014) analysing suitable strategies for planning on the community level.
- 2) **Urban Energy Networks** concentrates on the intelligent planning, design and operation of thermal and electrical networks in cities. Integrating distributed renewable energy sources into existing energy grids (thermal and electric) requires the development of smart urban energy networks. This sub-programme shall optimise the urban grids in order to provide flexible balancing potentials. This will be achieved by developing models for optimal management of low impact "Smart Energy Districts" and solutions for smart integration of electrical and thermal energy production, storage and consumption at an urban level.
- 3) **Energy-efficient Interactive Buildings** aims to analyse the role and added value of energy-efficient interactive buildings for Smart Cities and develop a knowledge platform for methods, solutions and cases that contribute to their large-scale penetration. This activity includes development of a common definition and vision, Key Performance Indicators and assessment of added value and cost for energy-efficient interactive buildings, development of adequate policy and market instruments to foster demand for energy-efficient interactive buildings, analysis of feedback from case studies to validate (or discard) existing KPIs, models and tools, and exchange of knowledge and experiences among sector stakeholders. The sub programme requires a robust framework that supports interaction between different physical scales traditionally governed by distinct research groups: from materials, technologies and buildings to urban districts, networks and energy grids.

- 4) **Urban City-related Supply Technologies** addresses renewable supply technologies and their integration into the urban infrastructure. The development of smart integrated energy networks will require new components and systems, as well as new approaches on the integration of distributed supply technologies into urban infrastructure.

In an effort to identify what needs to be researched now, to help cities reach their long-term energy vision 20 years ahead, EERA Joint Programme Smart Cities has created a City Advisory Board consisting of up to two municipal representatives from each partner country. Together with the City Advisory Board, development of the right key performance indicators and the right monitoring methods to help cities in their transformation towards a comprehensive energy roadmap was defined as an important research gap across all four sub-programmes.

One key element in this gap is the integration of buildings into the urban energy system – bottom-up as well as top-down – as buildings and energy grids tend to be managed by different sectors and disciplines and common goals, data, indicators and monitoring methods and tools are lacking. Important dimensions for design and operation of buildings as active optimal components in the energy system of the Smart City are definition of optimisation parameters, available flexibility, building typologies and the design /renovation process, potential integration of renewables / mix of energy resources, required comfort and expectations regarding user behaviour, expected development of usage over the lifetime of the building, the robustness of the energy system, systems for forecast and load management, business models, and national policies. A question of particular interest is what happens around 2020 when all new buildings according to the European Performance of Buildings Directive will have a near zero energy standard (EPBD, 2010)? When all buildings need to generate part of their own energy, interaction with the grid and with other buildings becomes a core issue.

EERA Joint Programme Smart Cities is working on closing this gap through a series of cross-sub programme workshops on topics such as Key Performance Indicators and monitoring, using cities as living labs; energy systems integration; urban energy-mobility interplay; real-time city operation and control; and simulation platform development. In Autumn 2015 EERA JP Smart Cities will host a European symposium on Key Performance Indicators for Smart Cities.

Project READY

The project *Resource Efficient cities implementing ADvanced smart citY solutions* (READY), (EU READY, 2014) is a collaborative project with a predominant demonstration component. The project is anchored in the municipality of Aarhus (Denmark) and Växjö (Sweden) but involves a total of 23 partners from four EU countries including housing associations, universities, energy sector and different industries and service companies. The total budget is 33.5 mill €, with funding of 19.2 mill € from the EU research and innovation programme FP7. The project kick-off was in December 2014. The motivation of Aarhus municipality to participate in the project is a vision of having a carbon neutral city by 2030. One of the strategies to live out the vision is titled *The Intelligent Energy System* where the ambition is to be a leading city in the development and test of intelligent energy systems, from simple low-tech to highly sophisticated solutions as well as the required market mechanisms. The scientific objective in READY related to building interaction with the energy system is to develop a replication platform for identification of the cost optimal solution for buildings in a city district, i.e. the trade-off in investments in energy savings (including embodied energy), renewable energy production, and demand-side flexibility technologies while ensuring high-quality indoor climate for the end-user. Another scientific objective is to identify business models for utilization of demand-side flexibility, i.e. creating an economical win-win situation for the renewable energy-based suppliers and the flexible consumer. A main hypothesis of READY in relation to building interaction with the energy system is that investments in methods and technologies for activating the potential for energy-flexibility when retrofitting an existing building is a viable alternative to investments in energy savings and renewable energy

production. The methodology is to use the predominant demonstration component of the project as a test bed for identifying, developing and testing the potential of methods and technologies for energy-flexibility of buildings. These experiences are used in the development of the replication platform.

ZenN Near Zero Energy Neighbourhoods

The Near Zero Energy Neighbourhoods project (ZenN) plans, executes and monitors demonstration projects on energy-efficient renovation of large-scale housing blocks in four countries: Norway, Sweden, Spain, and France. The project is led by Spanish Tecnalia, funded by the European 7th Framework Programme, and runs from 2013 to 2017. Norwegian partners are the Norwegian University of Science and Technology (NTNU), SINTEF Building and Infrastructure, and Omsorgsbygg Oslo – the latter as building owner of two of the ZenN demonstrators. In addition to the demonstration component, ZenN has embedded research-based work packages to support, monitor and analyse the development of the demonstration projects. The feasibility of the demonstrators is analysed through technical as well as non-technical dimensions; the latter comprise amongst others architectural quality and cultural heritage, social and stakeholder involvement, economic and business models, and governance frameworks. One of the first actions of the project was to interview key stakeholders of renovation and new building projects with comparable characteristics, to learn as much as possible about best practices and avoid serious mistakes already made by others. Some projects start with high ambitions and the best intentions but do not achieve successful results, while others have low ambitions despite good technologies being readily available on the market – what happened? The interviews identified important barriers at the decision-making level in renovation projects which did not have high energy efficiency improvement goals, and extracted challenges in the practice of the retrofitting processes in renovation projects with high energy efficiency goals (Karlsson, Lindkvist, & et.al., 2015).

In addition to technical and non-technical dimensions, the role of training is highlighted as nZEB ambitions require that partners, professional and end users fully understand the targets and their contribution to achieving these, learn new techniques and approaches, and discuss the challenges that arise in their daily practices in the demonstrators (Lindkvist, Shahin, & Wyckmans, 2015). Communication is important not just with their direct peers but with all stakeholders in the demonstration projects to achieve the cross-sectoral synergy effects that are needed to be able to realise the full potential embedded with energy-efficient renovation beyond the individual building scale.

National research and demonstration activities

In addition to the international research, development and demonstration activities, national projects are supporting this research agenda. Here some examples where the authors are involved.

Strategic Research Centre CITIES

The Centre for IT-Intelligent Energy Systems for Cities (CITIES), (Madsen et al., n.d.) is a strategic research endeavour with a budget of 71 million DDK and a public contribution of 44 million DDK, involving 40 partners from universities, cities, public organisations, industries and interest groups, both national and international. The motivation for the work is the Danish target to achieve a 100% CO₂-free society in 2050 as well as the global tendency towards urbanization, mentioned above.

The project targets the overall energy system of cities, just peripherally looking at the energy aspects of water, transport and others. Beside social, commercial and educational goals, the scientific objective is *“to develop methodologies and ICT solutions for the analysis, operation and development of fully integrated urban energy systems. A holistic research approach will be developed that aims to provide solutions at all levels between the appliance and the total system, and at all time scales between operations and planning”*, a very wide objective targeting almost all aspects of the energy system.

The basic idea is: *“Intelligence is the key to accessing this potential; communications, control, optimisation, forecasting, and data will facilitate the modelling, operation and planning of an integrated energy system with the required flexibility to ensure that energy supply and consumption are reliably and economically efficiently matched. Crucially, the flexibility allowed by energy system integration is not limited to hourly or daily time scales, but extends to the seasonal scale, for example, seasonal storage of wind energy by intelligent use of the gas/power systems in combination with CHP plants”.*

The project is organized in work packages, one for the coordination, two for the energy demand aspects, four central research projects on the cross-domain aspects of the energy system, one for the energy marked aspects and a final work package for innovation activities. The central four packages spread from operational short-term prediction to long-term planning and from individual components over cities to the continental electrical grid. Further work packages are dedicated to communication and innovation.

Because of the cross-domain research challenge, whole city cases are chosen as the mode of work. Hereby most aspects of the common tasks are exhibited and cooperation is promoted between researchers and domains. The idea is to collect as much data from the individual systems as possible. A first common city case is defined around the town of Svendborg that has been a front runner in CO₂ emission reduction targets, aiming at achieving CO₂ neutrality in 2029 before the national targets. The case is characterised by the variety of the energy systems that involve electricity, a number of local district heating and cooling, solar heating and PV and a planned, off-shore wind park. Similar, complementary towns will be added to the research in time.

Within CITIES, a work package is dedicated to the subject of how buildings impact the overall city energy system. Current work by Gianniou et al. is performed on the subject with mathematical simulation of aggregated building energy demands on a district and city level (Gianniou, 2014). The proposed methodology is to categorize the buildings, model the individual building types in detail and aggregating them to the wished cluster level.

Not yet published work is on the subject of finding the flexibility that is expected by the thermal mass of buildings. These capacities are expected to be utilized for energy demand shifting. However, this mode of operation is very slow compared to the fluctuations in the production of renewable energy. Hence it is relevant to investigate how much of the theoretical potential can be activated in time-limited periods with potential renewable energy surplus. Many of the building simulation models are simplified with respect to the storage capacity of the thermal mass and hence are not applicable for the evaluation of flexibility. The reason for this is that the models are based on theories that are not able to cope with such dynamics due to simplifications. Papers that are published today are often not considering these limitations. Actual work is ongoing to re-evaluate building simulation models with respect to time

EnergyLab Nordhavn (Copenhagen)

The "EnergyLab Nordhavn" is a national research, development and demonstration activity with a budget of 129 million DDK, including 53 million DDK by public funding. The project started the 1. April 2015 and hence there are no results to be reported yet. The motivation of the project is to meet the energy target of the Copenhagen Municipality to be the first CO₂-neutral capital in the world in 2025. The objective of the project is towards demonstrating a full-scale district: *Development of a coherent flexible energy system (electricity/thermal/transport) with novel technical solutions like energy storage by variable district heating temperatures, dynamic grid topology configuration and more integrated markets where infrastructures are closely interconnected and operationally co-optimized - enabling flexibility for integration of more renewables with stochastic nature (wind, solar etc.).*

From a scientific point of view, the Nordhavn project can be seen as a "living laboratory" experiment where solutions are demonstrated and monitored to gain experiences, build up and validate simulation models for this area and more. Even though there is no correlation between this and the CITIES project, data will be delivered to the CITIES research project to build models for the Nordhavn case.

The objective is *“research based, innovative technology development ..., while generating new methods, tools and theories for future smart energy systems integrating multiple energy infrastructures (electricity, heat, cooling, transport). This is done through predictive and partly automated solutions, optimizing the*

operation of systems components, such as buildings, cars, storage facilities, thermo-electric solutions (e.g., heat pumps), district heating and the electrical grid.

The Nordhavn project is especially focused on evaluating and controlling the flexibility potential of different technologies. The basic idea is to find the potential flexibilities, establish simulation and control models, optimize the overall system and predict the coming market for flexibility and cross-carrier trades. Also in this project, the investigation of the potentials provided by buildings has its own focused work package. The theoretical work, carried out in CITIES will be supported by collected evidence from the Nordhavn project. It is expected that two office buildings and approximately 50 living units will be monitored in detail.

As mentioned, the EnergyLab Nordhavn is a sea-fill bare field development. The neighbouring area of Oesterbro (called Nordhavn land-side) is planned to supplement the research and developments for the Copenhagen city with respect to an existing city district. It is expected that these activities will get research grants in the following period and hereby enable a complete “living lab” with new and old city areas.

Grid Ready Buildings in VPP4SGR

The project *Virtual Power Plant for Smart Grid Ready Buildings and Customers* (VPP4SGR, 2014), is an applied research and development project with a budget of 11.2 mill DKK whereof 7.5 mill DKK is support from the Danish national research programme ForskEL. Denmark aims to phase out all fossil fuels in the energy supply system by 2050. The motivation of this project is the intermediate goal towards fossil fuel independence: more than 50% of power will come from wind turbines in the grid in 2025. This stresses the need for demand response systems to accommodate the fluctuating electricity generation from wind turbines. The scientific objective of VPP4SGR in relation to building interaction with the energy system is to make a feasibility study on the use of model predictive control for realization of the energy-flexibility potential of a large low-energy residential building complex taking into consideration disturbances like user behaviour and weather forecasts. The main hypothesis is that low-energy buildings are able to provide valuable demand responses to the energy supply system without violating indoor climate constraints. The methodology is to make simulation-based studies on the demand response potential of the building and then to make full-scale tests on how much of this theoretical potential that can be realized. The value of different demand responses is analyzed, and recommendations on how to construct future smart grid-ready buildings are made.

Summary

Building research has traditionally been focusing on the goal of defining energy efficient solutions that ensure a good indoor environment in an economically sound manner. Due to the increased application of renewable energies in the grid systems, buildings are to support energy efficiency for the overall energy system. This implies a number of uncertainties that are to be investigated in research and development and utilized for innovative activities.

Cities seem to be the organisational and technical frameworks to tackle these issues. Hence many smart cities initiatives see this challenge as their motivation towards a sustainable future. Research has to face this challenge and address the many aspects that arise in city and energy planning which aim at knowledge based decision support.

The above research agendas point at the demand for research on almost any aspect, amongst planning methodologies across domains, demand for defining key performance indicators for the evaluation of changes, standardisation on any level of the city systems, cross-domain modelling and simulation methodologies for system analysis and decision support and demand for business models that occur due to the fact that city wide optimized solutions may affect economical distribution across partners, actually targeted through proposals for new marked models.

Cross energy carrier technologies and control solutions are to be found where the individual energy systems support each other, e.g., by allowing wind energy to be stored in district heating systems through heat pumps.

For building research, the objective has changed from single building energy demand towards the buildings in their contexts. A first tendency towards this can be found under the topic of microclimates that target the buildings' impacts on its neighbours and vice versa. This can include shading, wind and noise effects. In a smart cities context, the impact of the building is related to districts and whole cities, dependent on which aspects one is investigating, e.g., electricity will impact the regional energy system, whereas district heating connected buildings will impact this geographically limited system. One effort is to find methodologies to determine the impact of many buildings on the energy systems. To be able to validate such models, data at certain aggregation levels are needed which bring "privacy" issues into the subject.

On the individual building level, common research questions could be: Will building design and building codes change due to the demand by the surrounding energy system? How are the design methodologies to be adjusted? How can building models be combined with the surrounding energy system models?

On all the mentioned system levels, information sharing, "IT-intelligence" and controlling are the game changing mechanisms. Data have to be collected by sensors, these data shared through IT-networks and transformed into control forecasts by computing and communicated to the relevant system components, e.g. building neighbourhoods or whole business markets. Hereby building energy systems have to be adjusted networked intelligence, BMS and CMS systems to be able to communicate with other systems and control systems must be able to cooperate with other control systems and/or obey external control signals. Building information models will probably have to interact with real time monitoring and control systems. The common tendency is that buildings are active components in energy systems or even larger contexts (of districts and cities).

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