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Change in design targets for building energy towards smart cities

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Abstract: Designing cities from an overall energy optimization system point of view, demands changes in engineering procedures. Traditionally the design was driven independently between the involved domains and energy system components. By modelling the whole energy system in one, it is expected that there are exposed solutions where synergy effects arise that unleash extra saving potentials. Based on the insight gained by the simulations, IT intelligence and cross-component communication are to be invented to control the components and hereby to optimize the total system performance. One main strategy in doing so is, to move demands from high demand periods to low demand periods and hereby to avoid "peak" demands. This is called "flexibility" within the terminology of "smart grids". In early solutions the search was for energy capacities within the domain of the electrical grid, hence car batteries where seen as relevant solutions for providing flexibility. However, it seems that the demand is too large for electricity-only solutions. A next search for flexibility is aimed at finding electricity-thermal energy solutions such as electrical heating and cooling, heat pumps and cooling technologies that can help to stabilize the el-grid. To acquire even higher potentials, thermal system components are studied these days upon their flexibility potentials, such as heating and cooling of whole building structures. Hereby the question arises, how much "flexibility" there is in relation to the thermal capacities of buildings that enable shifting energy demand for heating and cooling over periods of hours? While the availability of these capacities is a topic of current research, the consequences for building design are obvious. While we in the past could focus on energy optimization, we now have to design our buildings to its context, offering flexibility to the surrounding energy system. No final answers are given due to the fact that this is the edge of current research in this field, while a first concept draft is presented here.

Keywords: Building design, flexibility, thermal capacity, energy optimization, city design.

Introduction

In traditional energy systems, the production side was adjusted to meet the fluctuating demands by different means. The future energy system is characterized by a very large or even 100% penetration of renewable energy sources that replace the rather stabile production side with a massively fluctuating alternative. Hence both the production and the demand side of the energy system will be fluctuating. In a first attempt the electrical distribution system was strengthened to tackle the challenge of stabilizing the overall system, the "smart grid". Recently, this idea of tackling the challenge within the electrical grid only, is replaced by a more multi stringed system design that includes gas-grids, district heating and cooling as well as the buildings into the solution.

In Denmark the penetration of renewable electricity from wind farms can be up to 100% for a few days. It covers in some areas over half of the production, while on a national scale share is approx. 33% [1]. All this is possible due to the fact that the national net is connected to other countries nets and hereby the capacities are shared. In a future net this will not be possible due to the fact that neighboring countries are expected to have similar climatic conditions and hereby will produce renewable energy in the same pattern as Denmark. Hence new more robust solutions are to be found. Obvious, additional potentials for stabilizing the electrical grid are, large grids such as the gas grid and district heating, and utilizing the energy demanding industries. Also the very large mass of the building stock could play a major role, if the mass is available for storage. This is the case if the mass is available for control but is absence in case of e.g. light constructions and inside insulated buildings. Research is ongoing to reveal the utilizable capacity of buildings. In the current work, the question discussed is, how future buildings could be designed to meet the demand for flexibility by the overall energy grids and smart cities. The reader will not find the answer, but rather a proposal for a methodology that in later work will be applied for the answering of questions about available and controllable thermal mass in building and the resulting flexibility available for the smart grid. Similar issues will be the kernel of an upcoming [2].

The Expected Fluctuations

Given the conditions of a future el-grid with large share of renewable energy sources for production, a balancing of the whole system is critical. The demand for electricity compared to the wind production for a few days in December 2012 for the Danish electrical grid in Jutland, Denmark, where renewable energy from wind mills can be dominating, is shown in Figure 1.

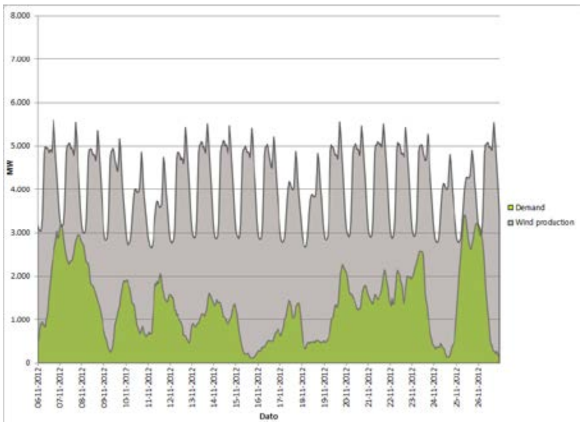

Figure 1 Demand and wind production for Jutland, Denmark for 2012. Source: [1]

A simple prediction for the corresponding curve for 2050 is shown in Figure 2.

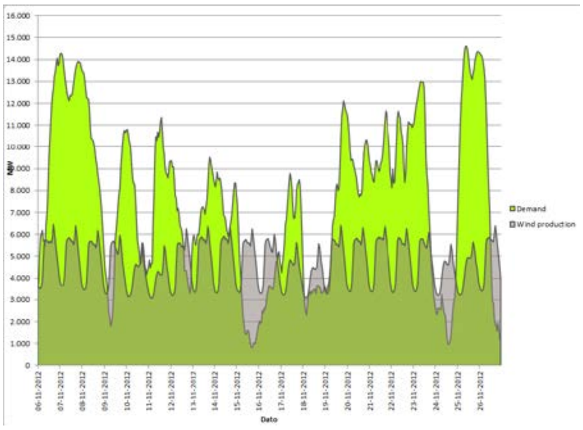

Figure 2 Demand and wind production for Denmark for 2050. Source: [1]

The above figures give an idea of the magnitude of the fluctuation and hereby the demand for balancing. The current paper reflects on, whether building can be part of a stabilizing solution.

This is done by modelling the buildings within the energy grids and compute relevant scenarios. Hence the modelling of energy demand for whole cities and more precise building stock in cities is the focus of the current work.

Limitations of current city level model

Searching research literature on city energy modelling will reveal that the basic idea behind such efforts was to simulate each building individually and sum up to the aggregated level of a city or a district. This approach enables the modelling of any buildings in accordance to the knowledge available, adjusted to the given case. This makes it possible to automate the parameter specification on basis of e.g. national building databases. Theoretically this approach is very precise; however the lack of detailed information does limit the precision of this procedure. To move from the individual building to the city, in many cases there are applied simple sums [3] and [4] where in other publications weighting factors where applied that reflect e.g. the gross area of the building or the Energy Use Intensity (EUI) [5] discussed below in the current paper.

The limitation of computing each building individually is that the simulation of many buildings takes a lot of computer time. To solve this problem simplified building models are applied that are not able to capture the dynamics necessary to find flexibilities in the building masses and additional storage capacities. Therefore an alternative approach is necessary to analyse solutions to the peak shifting problem. There is a need for simplified building models that reproduce the dynamics relevant to flexibility estimations realistically.

Building modelling for the smart city

Before going into details with the discussion of building energy simulation models, the aim of doing so must be defined. Existing models are designed for historical and actual building technologies. For future buildings the details of design are wake known. Hence the models can be designed rather abstract, catching just the relevant characteristics of the future buildings for scenario modelling, analysis and such like. This opens for the implementation of computationally efficient models. In the current paper, we will build on existing modelling methodologies and just mention what future developments could be.

The paper will propose a methodology to find the flexibility which buildings can offer to the surrounding energy system. More precise, the challenge is to find how much of the thermal capacities can be utilized in the demand shifting within buildings? The methodology is basically defined by the following steps:

1. Decide on a typology for the city buildings
2. Model each type by a dynamic simulation program (e.g. Energy Plus, IDA ICE)
3. Evt. apply stochastic distribution on each type

4. Represent all buildings in the city by the types computed and aggregate the results (e.g. flexibility) by different means discussed below.

The advantage, compared to the individual modelling is the ability to model a large number of buildings by just computing representative types and hereby very fast computations. The drawback is the uncertainties that the method introduces. However, other stochastic uncertainties, such as building context and user behaviour, are in similar magnitude and we must accept these uncertainties and find solutions to them by stochastic means.

In the below text, the different steps are described and discussed to define a methodology that can be analysed in future work.

Step 1 – Typology

You find different terms for what we call here “typology”, such like archetypes and classes, which are a classification of buildings into alike types with respect to certain criterions.

The goal for finding the current typology is, to classify the building stock systematically into types that represent many similar buildings in cities. Due to lack of knowledge on flexibility, which we aim at in a future work, we will here build on typologies that aimed at energy demand issues.

We did not find a comprehensive typology that is covering all buildings. The authors did often focus on a special subset of buildings such as residential buildings, offices and so on. Here is a short presentation of the findings from literature:

The European Union proposes a typology for residential building based on Eurostat data, with the three types covering 70% of the building stock in the included countries: *(a)* Single-family houses (including two-family houses and terrace houses), *(b)* Multi-family houses with more than 2 units and *(c)* High-rise buildings with more than 8 floors. In this typology, Europe is divided into three climate zones according to the degree days for heating and cooling. The methodology leads to 53 building types. [6]

Another approach is implemented for a few European countries in the web tool Tabula. The typology is country dependent which can be discussed to be arbitrary or methodologically significant. Within the given country the age of the building (construction traditions) and a clustering into the same types as in the previous source added a fourth type *(d)* Terraced Houses, leads to a matrix of building types for each country. On top of this, there are defined three levels of maintenance/renovation, (i) the original (ii) a “usual refurbishment level” and (iii) an “advanced refurbishment level. The technical installations and the thermal installation levels are defined according to the local traditions. [7]

Buildinglessons.com is an UK web site presenting the domestic, educational and other building types, all in all 22 building types. The buildings are described in IES<VE> models that describe the buildings in very detail and enabling standardized simulations. In case of applying other simulation software, this may be a weakness and a standardized description in on of the Building Information Model would be preferable.

The U.S. Department of Energy (DOE) has developed an online resource that defines 16 types of commercial and 5 types of residential buildings covering approx. 70% of the US building stock. [8] The DOE typology does also define “Technology descriptions” for e.g. lighting, heating and so on.

From these building types various methodologies are proposed that employ weighting factors to give a representative value for the energy demand of the building types. Within the technical report of NREL, [9], the combination of buildings and locations is proposed assembling the climatic and geographical effects in each building. The national data from the Commercial Buildings Energy Consumption Survey, [10], can be applied to determine the appropriate, average mix of representative buildings.

Other typologies that basically combine the mentioned methodologies can be found for non-residential buildings in [5] for the London area, [11] for the Keihanshin metropolitan area in Japan and [12] and Swan and Ugursal, [13], propose an archetype typology.

Step 2 – Dynamic simulation

The above mentioned typologies are often defined with respect to energy demand on a yearly basis. The computation of these energy demands can be done in many ways spreading from simple lookup algorithms to advanced dynamic simulations and even involve Computational Fluid Dynamics (CFD) computations. In the Tabula web tool, every country applies its own methodology, tool or computer simulation program. In BuildingLessons, the simulation program IES<VE> is utilized. For UK typologies a standardized methodology is defined in the NCM activity database on www.ncm.bre.co.uk. Here there are 29 building types with a classification of 505 room types, specifications for user profiles, temperature set points, ventilation rates and much more that aim at standardizing the simulation conditions rather than to standardize the model tool.

As the aim for the mentioned simulations is the energy demand on an annual basis, for the current purpose of estimating flexibility, a building energy simulation program must be found that represents the thermal dynamics of building constructions. There seem to be traditions, to apply finite difference/volume models or thermal response models [14]. Due to the fact that the latter do represent heat conduction by wave representations, e.g. Fourier models, the understanding of the basics is much more close to the human understanding. Hence such models can be applied for also abstract modelling of systems that are theoretically designed to have certain behaviour – let's say you will model building constructions with slow or fast heat exchange at the surfaces (e.g. thermo-active elements). The first will have a very slow wave – representation of the heat conduction, as the later has a fast wave model applied. The drawback of this approach is, that you cannot plot the temperature curves within a given construction and hereby it is difficult to see, how the heat is conducted and absorbed.

Step 3 – Stochastic distribution

The basic idea in this step is to represent the variability over buildings performance due to uncertainty in input parameters such as thermal properties of building fabric and also variation in user behaviour.

The two tools SunTool [15] and SimCity [16] have implemented such models, amongst for the user behaviour.

There are basically two ways to implement this stochastic, a) to use distributions on the individual parameters in the model, or b) coat the final building results by a distribution model. The first will give the possibility to use different distribution models for many aspects to be modelled. The later however is rather simple and fast. The idea could be to model the building types of a given topology determine the variability and use stochastic models to catch the stochastic aspects of among others, users behaviour and building context (shading, heights etc.).

Step 4– Aggregation

The aggregation is the step where one computes the impact of many buildings to a city level energy result. In literature you find very simple aggregation models for energy demands for building clusters. These models can be applied to flexibility aggregation also.

Many authors do not model the demand but rather base the energy demand on statistical data and distribute them to the buildings on basis of e.g. Energy Use Intensity (EUI) expressed per square meter floor area. [5] and [11].

An alternative method is a simple sum of the given

key performance indicator [16]:

$$F = \sum_{i=1}^{n} f$$

where *F* is the flexibility for the whole city or population of buildings, *f* are the individual flexibility simulated for a given building/-type, *i* is a counter and *n* is the number of buildings/-type.

The second aggregation model does add a weight to the individual buildings which make especially sense if you apply it to building types.

$$F = \sum_{i=1}^{n} w_i f$$

where a weighting factor, w_i, is given to the individual building/-type.

As we find, the aggregations are very simple and often no stochastic variability is applied. However the two approaches can be combined and are combined in above mentioned work.

No model is found that represents dynamic energy consumption and an aggregation from few buildings to a large number of buildings.

Building Modelling for the Smart Energy City

What role do buildings play? It gets rather clear that the peaks are placed in the mornings and the evenings where Danish citizens are at home and do washing, cooking and such everyday tasks that demand electrical energy supply. Hence it can be argued that almost the whole peak load is related to the building performances.

In more detail, the demands in buildings can be split into demand for heating, cooling, ventilation, hot water, light and electricity for appliances, whereas the former can be supplied by thermal sources directly and will not have impact on the electrical demand peak. Let's assume that we have a system that supplies also thermal services by electricity which is the case for many buildings outside the district heating networks of Denmark. What will the possibility for flexibility be and how can we estimate it?

For this purpose the building models have to simulate the dynamic behaviour of the building, the thermal capacities of the constructions, the storage tanks and other thermal capacities within the building. Many simulation models utilized for energy demand computations will not be able to reproduce these thermal capacities due to simplifications as mentioned before.

Designing for the Smart Energy City

In this section the methodology proposed in this paper is summarized.

1. Find an appropriate typology for your urban area
2. Compute average energy flexibilities (the methodology is still to be defined)

3. Find appropriate stochastic models for observed variations from the average.
4. Add the overall flexibility for the whole urban area at hand.

Moreover there must be found a City Information Model that enables description of cities in a comprehensive manner. This must be addressed in the future work.

It must be remembered that flexibility can be delivered by other technologies than building thermal masses, tank storage and such like. There are capacities in district heating and cooling networks that can be used to generate flexibility, and there are electro-thermal solutions such as heat pumps.

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