Zero Energy Buildings

How technical PhD research can be implemented in the design development of holistic zero energy buildings through an integrated design process

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Zero Energy Buildings
- How technical PhD research can be implemented in the design development of holistic zero energy buildings through an integrated design process

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Det
Strategiske
Forskningsråd

Content **Page**

1. Introduction

Present report is developed under the auspices of the Strategic Research Centre for Zero Energy Buildings and is the editors' suggestion for "how technical PhD research can be implemented in the design development of holistic zero energy buildings through an integrated design process". This report contains the contributions from some of the PhD fellows in the research centre, and is part of the communication of the Research Centre's results to practice.

1.1 Integrated Design

Designing a zero energy building is a complex task with many parameters in play - parameters that are often interconnected or conflicting. It requires a fine balance between the many design parameters if the building is to meet the strict requirements to energy and indoor climate, without having to compromise on the quality aspects. A method to help structure this complexity and to help ensure that all parameters are properly balanced in the final project is the Integrated Design Process (IDP).

There are several versions of IDP (e.g. Knudstrup 2004[1], Löhnert et al. 2003[2]). What is important in this case is not the particular IDP or what the individual phases are named. What is important is that a multidisciplinary design team incorporates knowledge from several fields from the very beginning of the design process. E.g. design, engineering and architectural knowledge, as well as knowledge and experience from executing parties or other project stakeholders, depending on the type of project. It is crucial that calculations are informing the project along the entire process and that the different design proposals are continuously evaluated in relation to technical performance, the users, the architecture, etc. It is important that there is consistency between the calculations level of detail and the "design stage" of the project.

An essential element of this publication is to determine when in the design process a specific design strategy / technology should be taken into consideration, and when the final decisions must be taken (e.g. about which energy system to be applied, how it should be integrated, and what consequences implementing one strategy / technology rather than another will have in relation to energy, indoor climate, architecture, user behaviour, economy, etc.). Determining these "point-of-no-return" is important in order to avoid back-tracking or "symptom treatment", which is often devastating for both building performance and architecture. For a simple and widely applicable picture of the design process, we in the publication work with three main phases:

1. *Design criteria are defined*
2. *Design proposals are developed, evaluated and optimized*
3. *The design proposal is concretised*

The process is an iterative process where knowledge gained in the project's later stages can lead to adjustments in the project's earlier stages. The phases do not refer to a time wise linear process, but relate to different stages in the development of the design.

[1] Knudstrup, M-A. (2004) Integrated Design Process in Problem-Based Learning: Integrated Design Process in PBL. in The Aalborg PBL Model : Progress, Diversity and Challenges. ed. / Kolmos, Anette : Fink, Flemming K. : Krogh, Lone (eds.). Aalborg : Aalborg Universitetsforlag, 2004. pp. 221-234.

[2] Löhnert, G., Dalkowski, A., Sutter, W. 2003, 'Integrated Design Process - A guideline for sustainable and solar-optimised building design', International Energy Agency (IEA) Task 23 Optimization of Solar Energy Use in Large Buildings, subtask B.

1.2 Form of the contributions

The text below is a template for the PhD fellows' contribution to this report. The template might give an overview and an introduction to understand the form and content of the contributions.

When answering the questions below, it was important that the PhD fellows imagine the architect /engineer in his/her process of designing a new building, and that their knowledge about the specific technology was to be "translated" to be useful in the design process.

The questions were divided into seven main "themes", which we believe are areas in which the architect/engineer should have/obtain information about each strategy/technology in order to integrate this into a building design.

The seven "themes" were:

A. Problem

A shot description: what is the specific technology; i.e. what characterises it and how does it "work"?

What are the qualities/potentials of your technology (in relation to energy, indoor climate, architecture, user behaviour, etc.)?

What are the issues related to your technology (in relation to energy, indoor climate, architecture, user behaviour, etc.)?

B. Aspects in play

What aspects are in play when working with this specific technology? What different aspects (quantitative and qualitative) should the architect/engineer take into consideration when considering/implementing this technology, and what are the means ("instruments") that he/she can work with in order to meet both the qualitative and the quantitative aspects?

C. Frame of solutions

What different solutions on integration of the specific technology are there? Perhaps this relates to different scenarios (e.g. different locations, user groups, orientations of the building, etc.) that may suggest one solution rather than another.

What should one be aware of when working with (or implementing) the different solutions, e.g.:

- Efficiency (so that one can compare the different solutions)?
- Price?
- Net area (m^2) or the utilisation of this?
- Impact on daylight level/daylight quality/views/privacy/relation to the context/….?
- Impact on the façade expression?
- Issues/qualities related to maintenance/repairs/replacement/….?
- Constructional qualities/issues?
- Automatic control > < manual control?
- Potential conflicts related to the user?

- Are they suitable for single-family houses?
- ….

D. Built examples

Can we show examples? E.g. examples:

- Where one or more of the above described technologies are integrated,
- That illustrates how the technology can look like – and work – in practice,
- Of isolated components which have potential for being integrated.
- ….

(This can also be links to homepages etc. where the technology is shown)

E. Process

When in the design process do you think the architect /engineer should take into account the different aspects related to this specific technology (in relation to the 3 phases described: 1. Design criteria are defined, 2.Design proposals are developed, evaluated and optimized, 3.The design proposal is concretised? When are the first consideration to be taken into account, and when should the final decisions be made in order to avoid back-tracking or "symptom treatment" – i.e. when do you define "point-of-no-return"?

F. Tools

What tools are used for evaluating the impact of the strategy / technology, i.e. its impact on architecture and technical performance, and are these commonly known / used in practice today?

G: Economy

What will applying this specific technology mean to the economy of a given project? E.g. will it (always) mean an additional cost or will/can it lead to cost savings in the long run? This may also include considerations related to “construction costs” > < “construction costs + operational costs”.

This can be considerations on an overall level as well as more specific information if that exists.

2.1

Title of PhD project: District Heating and ZEB
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District heating for net zero energy buildings

When choosing the heat supply for a net zero energy building, some overall considerations must be made related to the location of the building. In general, the choice of heat supply will be a choice between individual solutions and collective solutions. This description focuses on the collective supply option in the form of district heating and why this, in many cases, is the best solution for net zero energy buildings (NZEB).

To be clear from the beginning, district heating is only an option in existing district heating areas or in areas where district heating is planned, and thus not everywhere. Figure 1 gives an idea about where district heating is an option in Denmark today. Denmark has 431 district heating areas supplying 61.7% of all households in the country [1]. The majority of these areas are operated and planned in cooperation between the municipality and the local heat supply company. The municipality can provide information on where district heating is available and how to contact the local supply company for specific information.

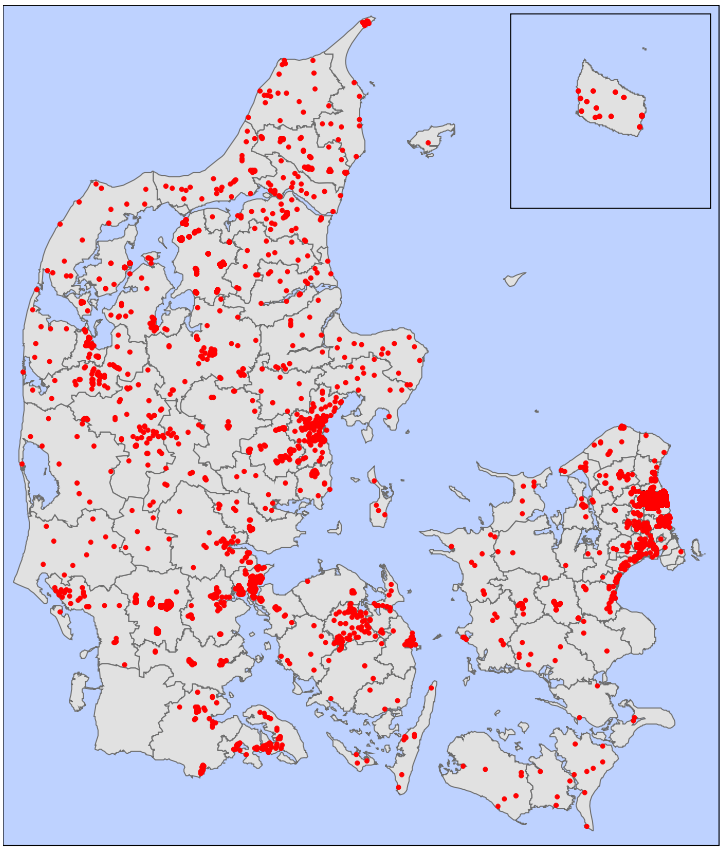

Figure 1: District heating areas in Denmark

District heating is different from one area to another, due to city sizes, the historic development within the area, as well as heat supply technologies and fuels available. In general, district heating is beneficial to an area in the sense that it utilizes heat from other processes such as electricity production, waste incineration and industrial processes. This helps to minimize the overall resource use, since the heat would otherwise be produced individually on the basis of other additional resources. Furthermore, district heating enables the use of renewable energy sources such as geothermal heat and solar thermal collectors, often in combination with large heat storages. Figure 2 shows the development of resource use in Danish district heating areas from 1994 to 2011. In the beginning of the period, the heat production was dominated by fossil fuels. Since then, the share of renewable energy has increased, mainly in the form of biomass, but also solar thermal, biogas and heat pumps. The resource consumption shown is the total for the whole country and each individual area has its own fuel mix. In some areas, this mix is based on coal while in others, it is based on biomass. When considering district heating for a net zero energy building, the fuel use in the area is important, since the building per definition has to be supplied by renewable energy. Another important issue related to resource use, is that, when calculating the energy frame for a new net zero energy building, a primary energy factor of 0.8 is used for district heating to compensate for the lower resource use. For more details on this, see [2].

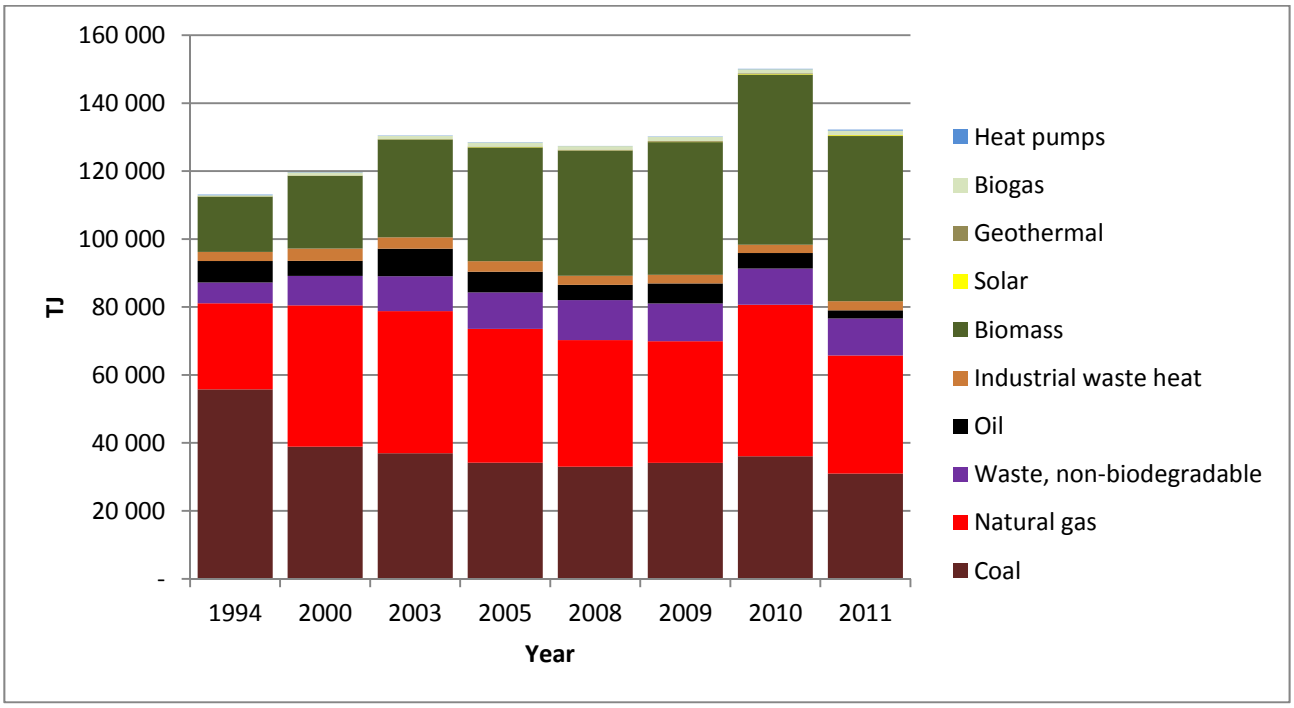

Figure 2: Energy consumption in district heating divided by fuels [1]

However, district heating is in a transition period and the current political target in Denmark is to transform the electricity and heat supply into renewable energy-based production by 2030. This includes an increased use of district heating, in which the production will be gradually transformed into using renewable energy, mainly in the form of biomass and large heat pumps [3]. District heating also has some disadvantages compared to individual solutions, mainly due to the investment in pipe systems and heat losses during heat distribution. In the current Danish district heating areas, the heat losses are in general between 15-25% of the produced heat. To minimize the losses and improve the technology, a lot of research is done within the

field of low-temperature district heating; visit the Research Centre for 4th Generation District Heating (4DH) for on-going information on this [4].

The differences between areas also influence the costs for the consumers, see Figure 3. The consumer costs vary significantly between Danish district heating areas, with the lowest price below 400 DKK/MWh and the highest around 1,600 DKK/MWh. Since district heating is a natural monopoly in Denmark, the prices are regulated by the Danish Energy Regulatory Agency to ensure reasonable price levels for the consumers. The district heating companies are not allowed to make a profit from the heat sales, so the consumers only pay the costs related with the operation of the district heating area; this is regulated by the specific rules in the heat supply law [5]. The price variations are mainly based on differences in the heat supply and the efficiency of the system, including heat losses.

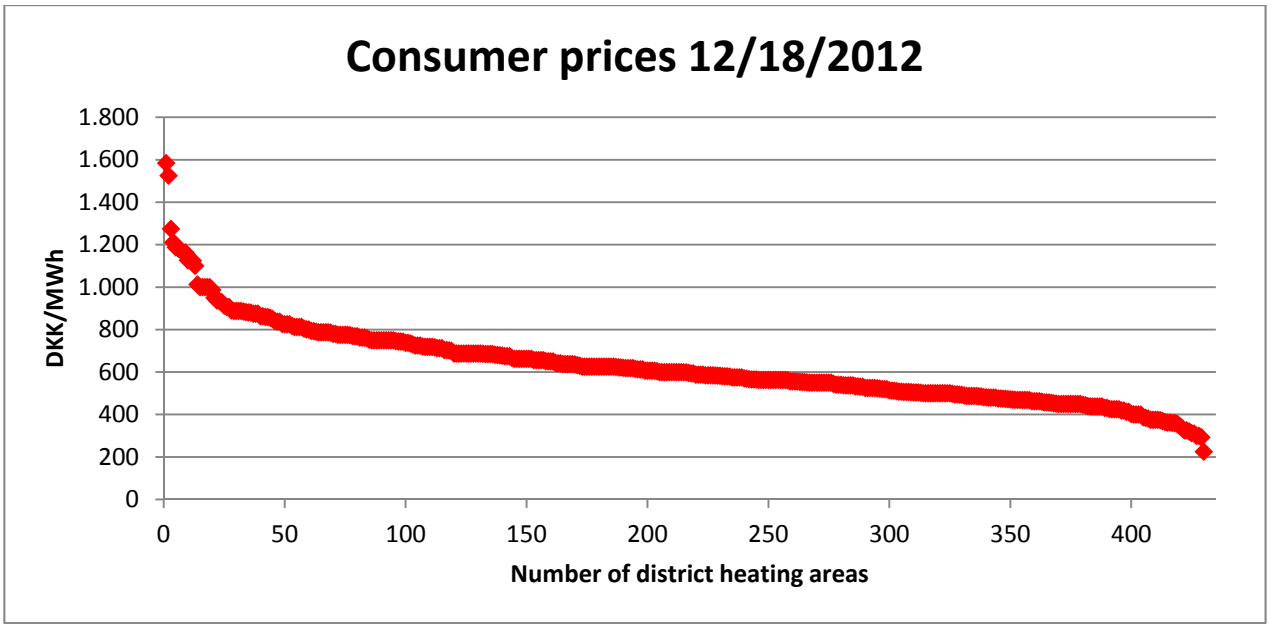

Figure 3: Average consumer costs in Danish district heating areas [6]

The prices shown are averages for each area; the individual consumer price depends on the tariff structure of the particular district heating area. These structures differ between district heating areas, but in general, most areas charge the consumers according to a fixed part and a flexible part. For the individual house, this means that a low heat consumption only influences the flexible part of the price, while the fixed part will remain the same as in the case of a high heat consumption. This is important to buildings with a low heat demand, since a large share of the price is not influenced by the low consumption of the building. Often, district heating companies offer different price levels depending on the consumer type. In relation to net zero energy buildings, it is important to examine if the district heating company offers different price options for this type of buildings.

One of the ideas behind NZEBs is to have renewable energy production in the building. One option is to use a solar collector on the roof in combination with district heating. Currently, this is not a commonly used solution, so it is strongly recommended to contact the district heating company to examine if they support solar production on individual buildings. For a more general view on this see [7].

In general, it is recommended that new net zero energy buildings within district heating areas connect to the collective supply, both because society's long-term goal is to use district heating and because district heating enables the use of a variety of renewable resources. In areas without district heating, it should be examined if there are any plans for the expansion of the district heating area. If this is not the case, an individual supply should be chosen. However, it is recommended that the internal heating system in the building is compatible with district heating, in the case that it becomes available in the area in the future.

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[6] Danish Energy Regulatory Agency, Heat price statistics, www.energitilsynet.dk/varme/prisstatistik

[7] Steffen Nielsen and Bernd Möller, Excess heat production of future net zero energy buildings within district heating areas in Denmark, http://www.sciencedirect.com/science/article/pii/S0360544212002927

2.2

Title of PhD project: Integration and optimization of renewable energy systems for housing

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A. Problem

The design of supply systems for Net ZEBs requires special consideration and adapted methods for determining the optimal system configuration. In Figure 1 five major challenges are depicted, which affect the supply system of zero energy buildings.

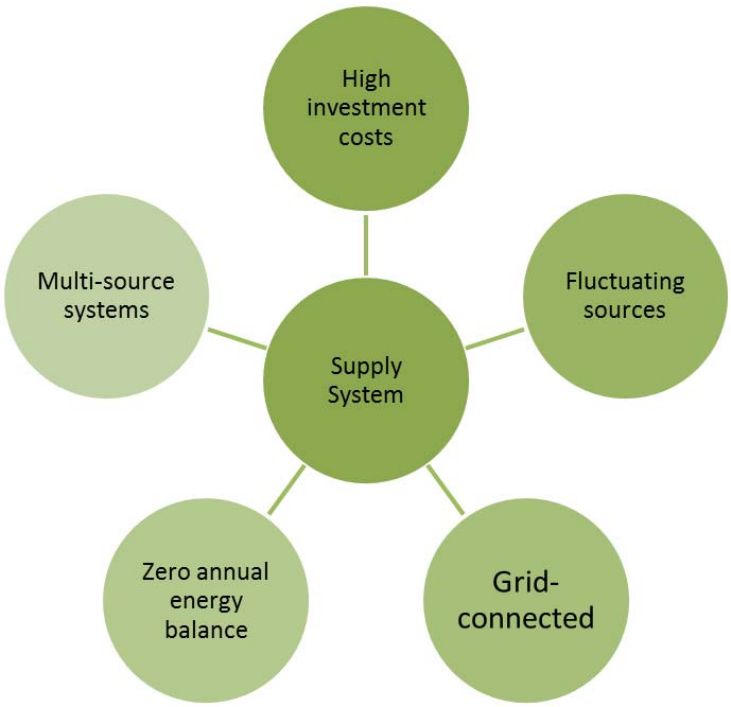

Figure 1 - Five major challenges in designing Net ZEB supply systems

Multi-source systems

In opposite to standard supply systems, which often consist of a gas boiler and public grid connection, Net ZEB systems have to rely on several different technologies to cover the whole energy demand. This leads in most of the cases to multi-source systems (irradiation, wind, wood pellets, etc.) instead of relying on one fuel, e.g. natural gas.

Fluctuating sources

Additionally, most of the renewable sources are fluctuating, e.g. irradiation, and therefore “non-controllable”. This has to be considered in the planning process to assure that the building energy demand is covered at all times.

Grid-connected

However, Net ZEBs are not island systems but are in most cases connected to energy infrastructure as to public grid or district heating networks. This allows for exchange of energy with the infrastructure and using it as a short time or even seasonable storage.

Zero annual energy balance

An important feature of Net ZEB is the required zero energy balance on an annual scale. Therefore, electricity or heat consumed from public infrastructure has to be delivered back within the actual year.

High investment costs

Besides the technical characteristics also the economic situation is different for Net ZEB supply systems. In general these systems are still more expensive and they cause very high investment costs compared to standard solutions. However, annual operation and maintenance costs are substantially lower and in some cases close to zero.

All these circumstances have to be taken into account when designing the supply system. No global solution exists and each building requires individual planning based on the on-site conditions of the building. As part of a PhD thesis a methodology is developed, which allows for a cost optimal system design based on specific conditions at the building site. It chooses and sizes the relevant supply technologies to meet the condition of a Net ZEB in a cost optimal way. The solution is based on hourly values of reference weather data as well as expected consumption data of the building. Furthermore, the system designer can specify certain constraints, e.g. a degree of yearly Net ZEB performance.

B. Aspects in play

Apart from the above mentioned challenges, several other aspects are affecting the optimal integration and operation of the supply system, as summarized in Figure 2

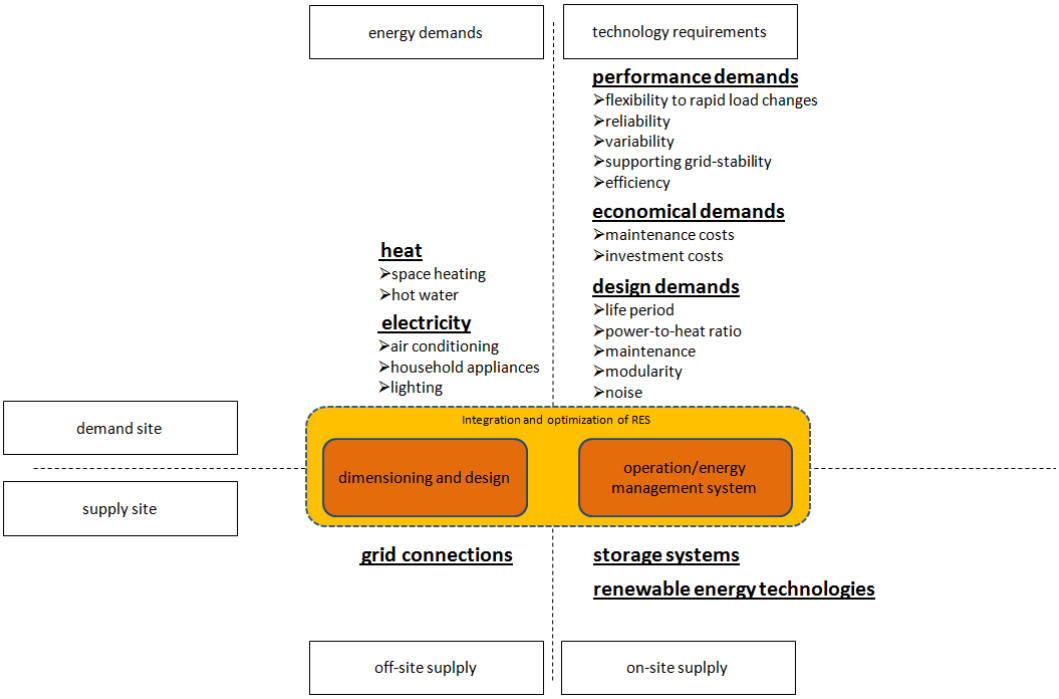

Figure 2 - relevant aspects in supply system optimization

The provided methodology addresses the different demands (energy demand and several of the technology requirements) and can be used by a designer/energy planer to design an energy supply system considering most of the aspects. It has to be stated that several of the requirements might contradict each other, etc. supporting grid-stability and maintenance costs, etc.

C. Frame of solutions

There is no general solution for an energy supply system based solely on renewables. This is also the starting point for the developed methodology. The solution depends mainly on site specific weather conditions and consumption profiles, i.e. building performance, user behavior, as well as the applied Net ZEB definition or building design (south faced roof).

First analyses have been carried out in a case study for a single family house in Denmark with two persons. However, as stated above, these results do not allow for a general conclusion and should not be seen as a statement for/against a single technology since the whole supply system is very interdependent.

All of the aspects mentioned in the chapter above are important and it depends on the designer which feature he assigns the highest priority to, e.g. price, efficiency, etc.

D. Built examples

The results of one example are shown in e.g. Milan et al, 2012 (http://www.sciencedirect.com/science/article/pii/S0360544212004148). A case study has been calculated

presenting a cost optimal supply system configuration. Experimental verification of a test system is in preparation.

E. The process

In phase 2 the energy supply system should be kept in mind, e.g. different building structures could be tested to minimize the energy consumption of the building and to optimize the position of the supply systems (south faced). In phase 3 the tool could still be used to evaluate different solutions and to choose the cost optimal one, but it is possible that the optimal solution lies outside of the design proposals. The point of no return is when the system components are bought and about to be installed.

F. Tools

No tools are known or used so far. But it is planned to conduct a study of existing systems, where trial and error approaches have been used and to see how much this configuration deviates from a theoretical cost optimal solution by applying the methodology.

G. Economy

The costs for applying the methodology are rather low, since the calculations take less than a minute for a single family house. Only costs for buying on-site weather data might occur but can be considered as non-relevant in comparison to the usual budget for constructing a building. The program allows for reducing the installation costs in an optimal way, since oversizing is avoided as well as the most cost-effective technologies are chosen for the particular conditions. Both, construction costs as well as operational costs are included in the calculations.

Own Publications:

(1) An optimization methodology for the design of renewable energy systems for residential net zero energy buildings with on-site heat production./ Milan, Christian; Nielsen, Mads Pagh; Bojesen, Carsten. In: *Proceedings of the 6th Dubrovnik Conference on Sustainable Development of Energy Water and Environmental Systems (SDEWES 2011*). 2011. Dubrovnik. *15 s.*

(2) A cost optimization model for 100% renewable residential supply systems./ Milan, Christian; Nielsen, Mads Pagh; Bojesen, Carsten. In: Energy 48 (2012) p.118-127

(3) Choosing the right technology – Optimized design of renewable supply systems for residential houses./ Milan, Christian; Nielsen, Mads Pagh; Bojesen, Carsten. In: Proceedings of the 11th international conference on sustainable energy technologies (SET 2012).2012. Vancouver, Canada. 12 s.

2.3

Title of PhD project: Optimal Building Integrations of District Heating Substations
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Marek Brand – Low-Temperature District Heating

Problem

Low-temperature District Heating (DH) is a part of the solution to reach fossil free heating sector by 2035 in Denmark, thanks to the effective integration of renewable energy and reduced heat loss from the networks. Low-temperature DH takes into account the reduction of the heat demand in low-energy and refurbished buildings which make traditional DH uneconomic. The key success factors are the low supply temperature of 50-60°C and the proper cooling of DH water.

There are two main potentials of low-temperature DH:

1) use renewable sources of energy (geothermal, solar thermal, waste heat, etc.) on low-temperature level and thus with higher efficiency than traditional DH while still provide buildings with enough heat for DHW preparation and space heating

2) use centralised renewable energy sources rather than the individual on-site production because of higher efficiency and lower cost

Nevertheless reducing the DH supply temperature brings challenges both from the perspective of DH users and DH utilities. The challenges are mainly related to:

1) heating of the Domestic Hot Water (DHW) – avoid risk of Legionella (i.e. minimal temperature of DHW, maximum volume for DHW storage, possibility to keep DHW circulation) and reduce waiting time for DHW produced with desired temperature [1]

2) space heating (SH) systems – design the SH system properly to provide required thermal comfort for the occupant while ensuring constant load on the DH network and low return temperature [2]

Aspects in play

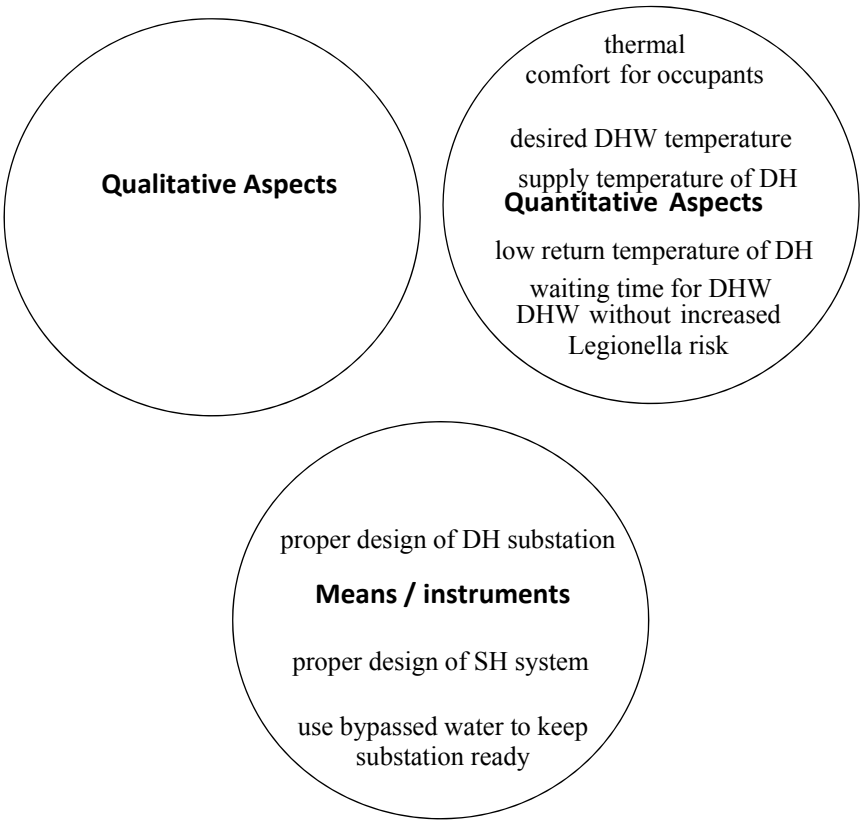

Figure 1 – aspects in play

Frame of solutions

There are two different types of low-temperature DH substations. First one is without a storage tank for DH water (Instantaneous Heat Exchanger Unit = IHEU) and the second one is with storage tank for DH water (District Heating Storage Unit = DHSU).

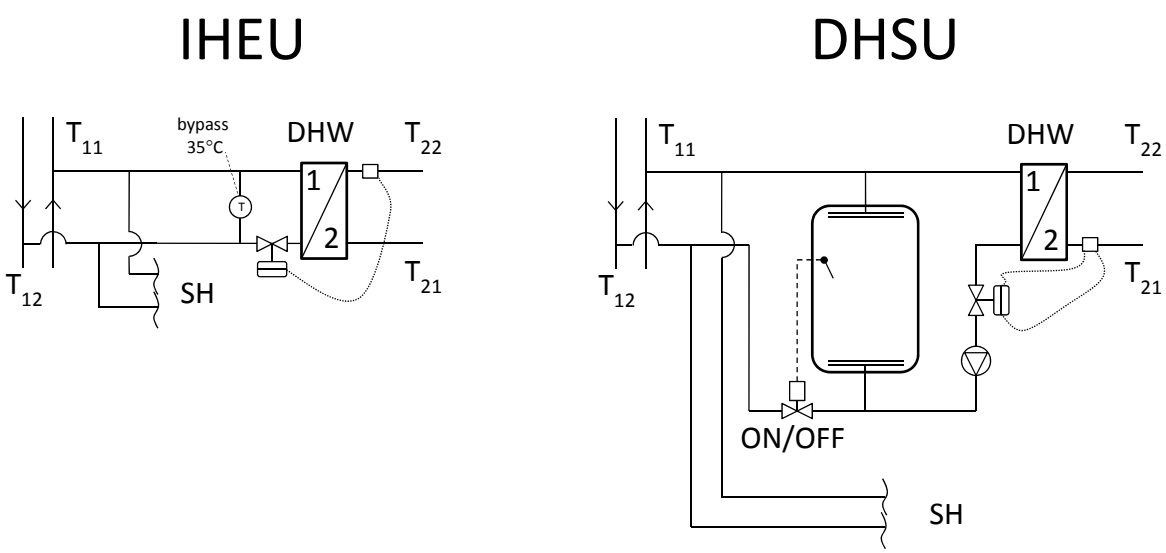

Figure 1 – principles of low-temperature DH heating substations, left IHEU [1], right DHSU [3]

There are three typical space heating systems to be considered: radiators; floor heating; forced air heating. Table below summarizes basic characteristic of DH substations and space heating system which needs to be considered already during the design phase.

Table 1 – characteristic of DH substation and SH systems

Low-Temperature District Heating		
DH substation for DHW preparation		**Space Heating system**
IHEU	**DHSU**	Importance of proper design conditions • use dynamic simulation • design low return temperature • heat demand without peak values
Not at the outskirts of the DH network	Outskirts of the DH network	
Need of bypass = possibility to use "comfort bathroom"	Higher heat loss from the substation.	*Radiators* Possible problems with small flows in thermostatic valves (temperature oscillations, noise)
Very small space requirements – compact solution	Space requirement for 120L storage tank	*Floor heating* Slower reaction to heat gains change (solar) *Forced air heating* In basic design air temperature can not be controlled individually in the rooms and causes thermal discomfort. Be10 – FAH can not be only SH system anymore

Built examples

There is only example of the low-temperature DH in Lystrup-Århus [4,5] in 42 single-family houses built in accordance with low-energy class 1 (Be08). 10 houses is equipped with substation with storage tank

(DHSU), the others without storage tank (IHEU). The houses are heated with radiators designed to 55/25/20°C and there is a floor heating in the bathroom with thermostatic control on the return pipe.

The process

Early in the process the architect should keep in mind to place all DHW taps as close as possible to the DH substation. The reason is to reduce waiting time for DHW before it reaches the tap, because in LTDH is suggested to avoid DHW circulation. If the suggestion is not followed it decreases comfort for the occupants and it leads to wasting of water (DHW with not proper temperature is usually flushed directly to the sink).

The decision about DHW heating principle is important during the design phase of the DH network. From the perspective of the house installations the only requirement needed to be considered is enough space to install the DH substation.

The decision about SH system should be taken in phase 2 (development of design proposals) because floor heating will have different requirements (composition of the floor, integration of heating pipes) than forced air heating (design of the ventilation system). It has also influences the design of DH substation, but it is expected in the last phase.

Tools

The tools are commercially available dynamic simulation software for calculation of energy demand in buildings, e.g. IDA-ICE [6]. The DH network can be calculated with TERMIS software [7].

Economy

An example of Low-temperature DH supplying settlement of low-energy houses class 1 has slightly better economy than individual heat pumps. The cost of low-temperature and traditional DH substation is for the house owner very similar, but traditional DH has 75% higher heat loss from the DH network, which makes difference in heat price for customers [4].

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http://www.byg.dtu.dk/Publikationer/Byg_rapporter.aspx

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[7] Termis – www-7t.dk

2.4

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Technology

Closed Loop Geothermal Heat Pumps – A Renewable Energy Technology for Heating and Cooling of Buildings: Single family residential houses applications.

Problem

Closed loop geothermal heat pump systems (ground coupled heat pumps – GCHP) are a sustainable and renewable energy technology that can be used to meet the energy saving targets of Net Zero Energy Buildings [1]. It offers economic and environmental advantages in terms of primary energy and heating/cooling cost savings, and CO_2 emission reductions, compared to conventional HVAC equipment.

GCHP systems can be adapted to different buildings and climatic locations, however, system design must account for the specific building heating/cooling load pattern and the local site conditions. These factors cause significant variation in the total cost of the technology.

GCHPs have three main subsystems, which can be designed in a variety of configurations:

- Source side system: the ground heat exchanger (GHE), allows heat transfer between the ground and the heat pump system. In heating mode heat is extracted from the ground and in cooing mode heat is rejected to the ground.
- Heat pump system: water (or brine)-to-water heat pump used to convert the thermal energy from to ground to a suitable temperature level required by the building HVAC system.
- Load side system: equipment inside the building transferring heat or cold to the conditioned spaces (the HVAC system).

Due to the dynamic coupling between GHE, heat pump, HVAC system and building, an integrated design approach is needed, matching the different components in a way that an optimal system which works efficiently in economical and technical terms can be achieved.

Aspects in play

A GCHP system design should follow an integrated design process for optimizing the energy efficiency and environmental sustainability of the technology. The main key factors in GCHP installations design are the energy profile of the building (heating and cooling demand), the heat pump, the ground heat exchanger, and the operational strategy of the whole system. The overall performance depends on the dynamic long-term thermal interaction between the source side (GHE) and load side (building and HVAC equipment) of the system. The local site conditions (available land area and hydrogeology) and building energy requirements (annual heating/cooling demands on the source side) determine the feasibility and most

cost-effective configuration of the GHE. The thermal response of the ground to the long-term heat extraction and rejection, is dependent on adequate GHE sizing, and determines the source side system's ability to deliver thermal energy within acceptable temperature range. Low temperature difference between the source and the load side of the system is desirable for achieving high energy efficient GCHP performance. Heat pump with nominal energy efficiency rating (COP/EER) within the corresponding source and load side operating temperature ranges will dictate energy efficient coupling between the GCHP sub-systems.

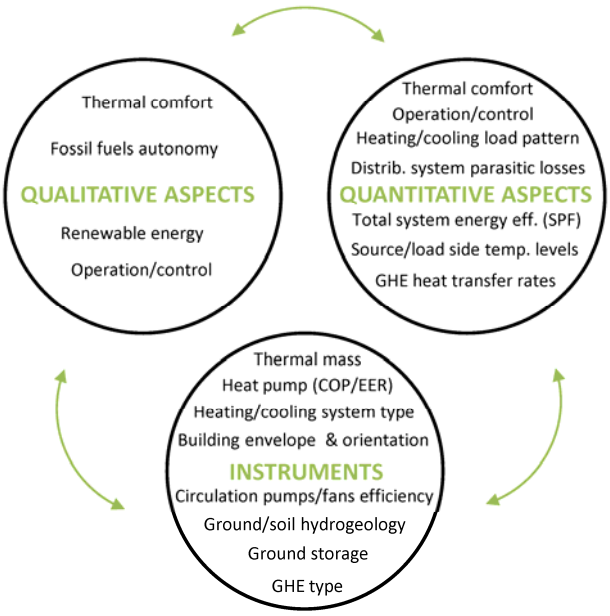

Figure 1. Diagram of aspects which need evaluation.

Frame of solutions

The ground coupled heat pump systems can be used from small residential houses (3-10 kW) to large commercial and public buildings (50 kW up to 1 MW). There are three main types of GHE designs used in residential houses, vertical, horizontal, and foundation GHE.

a) Vertical GHE (boreholes) **b) horizontal GHE** **c) foundation (sub-slab) GHE**

Figure 2. GCHP for residential buildings.

The type of GHE used will affect heat pump system performance, auxiliary pumping energy requirements, and installation costs. Choice of the most appropriate type of GHE for a site is usually a function of available land area, energy performance and life cycle cost economics.

Vertical GHE consists of single or double U-pipe (PEX-pipe) heat exchanger inserted in a vertical borehole (30-200m). Horizontal GHE is built of PEX-pipes buried in trenches, typically at a depth of 0.5-3.0m. The foundation (sub-slab) GHE is built as a PEX piping layer (10-30cm pipe spacing) embedded in a 0.1-0.3m thick concrete slab, thermally decoupled from the building ground slab by an insulation layer.

Vertical GHEs use underground temperature stability to maintain a satisfactory SPF of the whole system. For residential houses, the concept is generally considered when land area is limited. The cost of boreholes (drilling, backfilling, etc.) is a major drawback of the system.

Horizontal and foundation GHEs performances are directly related to local climatic conditions due to the shallow installation depths. The need for excavation and large land area are major cost and construction barriers for horizontal ground coupled systems.

Foundation GHEs have no land area requirements and have significantly lower investment cost compared to vertical and horizontal GHEs. However, due to the fact that the GHE should be integrated with the foundation work, conflicting with pipe installation may arise.

The capital cost of a GCHP system is higher than the cost of a conventional HVAC system (due to the earth coupling) and there are many factors that have to be evaluated to develop a long term energy and cost-effective system. The systems are considerably more efficient and economic when used for both heating and cooling. Primary energy and heating/cooling cost savings are related to the overall system performance. Subsystems dimensioning should aim at the smallest possible temperature difference between the source and the load sides of the system, which would result in the highest heat pump COP. Regardless of the type of GHE used, proper sizing should ensure the source side temperatures are as warm as possible during heating season and as cool as possible during cooling season. On the load side, low-temperature heating and high-temperature cooling hydronic radiant systems are best suited for fulfilling the low-temperature difference requirements. Parasitic losses, from circulation pumps and heat loss/gain from the distribution system, should be minimized, since they can alter greatly the GCHP system performance efficiency.

With residential buildings lifetime expectancy of 100 years, the expected lifetime of the GCHP system should be evaluated, in order to estimate the operation and maintenance costs of the system and perform LCA cost analysis. The typical lifetime of water (brine)-to-water heat pump is 15-20 years, with similar lifetime expectancy for the rest of the HVAC equipment at the load side. The ground side, regardless of the type of GHE, has an expected lifespan of more than 50 years. In terms of operability, the GCHP system is considered almost maintenance free, which results in very high reliability and low exploration cost.

Figure 3. Sunlighthouse, Austria [2]

Figure 4. Hope Crossing, OK, US [3] [5]

Built examples

GCHP are widely used for heating and cooling of low and net zero energy buildings. The solutions are often used in combination with other renewable and natural energy sources like solar thermal and natural ventilation. In Figure 3 to Figure 6 are shown examples of low and net zero energy houses equipped with ground coupled heat pumps. More examples and further information about the technology can be found in the included references.

The process

The energy efficiency of the GCHP system is directly related to the performance of the heat pump. All heat pumps improve their thermal efficiency (better ratio between delivered thermal power and used electrical energy) at small temperature difference between the evaporator and condenser side of the machine. At the load (building) side, as already mentioned, that would require the use of low temperature heating and high temperature cooling radiant systems. At the source side (ground), site investigation and GHE optimization will improve the operating temperature range and reduce installation costs.

Figure 5. Ideal Home, OK, US [4]

Figure 6. Muolen, Switzerland & Judendorf, Austria [5]

As a result of the above considerations, the potential use of a GCHP system should be investigated already in the early stages of building design, where the building designers (engineers, architects, etc.) have the highest possible freedom of decision making. That would ease the development of optimised installation concepts, operating strategies and controls that fully exploit the GCHP system potentials and qualities.

Tools

For evaluating the performance of GCHP systems, unified building simulation tools are used, which enable the building designer to evaluate the coupled 'ground heat exchanger – heat pump – building installations' system performance.

Software tools like EED [6] and TRNSYS [7] are commonly used in practice, which allow the building designers to evaluate, at different levels of detail and complexity, the performance of the potential sub-system configurations and different operation and control strategies, and ensure the integration of all factors and the energy efficiency and long term sustainability of the system.

Economy

The economic justification for GCHP systems usually requires that annual capital and operating costs are less than the cost for conventional systems and equipment supplying the same service loads and periods.

GCHP projects are associated with high investment cost, compared to conventional HVAC systems, mainly due to construction costs associated with the GHE. However, if properly designed, such systems can result in substantial reductions in operation and maintenance costs and respectively with favourably short payback periods, in comparison to alternative conventional HVAC equipment. The operational cost of the system is highly influenced by the price of electricity and fuels and by the efficiency (SPF) of the GCHP system. Additionally, a GCHP system is considered almost maintenance free. The above considerations show that a GCHP system can have very high reliability and low exploration cost. Moreover, reduced

equipment sizing on the building side can reduce the room required for building installations, and free valuable space for more profitable use.

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[4] http://www.nrel.gov/docs/fy08osti/40875.pdf

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2.5

Title of PhD project: An Integrated Control System for Heating and Indoor Climate Applications

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Problem

Low temperature hydronic heating and cooling systems connected to renewable energy sources have gained more attention in the recent decades. This is due to the growing public awareness of the adverse environmental impacts of energy generation using fossil fuel. Radiant hydronic sub-floor heating pipes and radiator panels are two examples of such systems that have reputation of improving the quality of indoor thermal comfort compared to forced-air heating or cooling units. Specifically, a radiant water-based sub-floor heating system is usually combined with low temperature heat sources, among which geothermal heat pump, solar driven heat pumps and the other types are categorized as renewable or renewable energy sources.

In the present study, we investigated modeling and control of hydronic heat emitters integrated with a ground-source heat pump. Optimization of the system performance in terms of energy efficiency, associated energy cost and occupants' thermal comfort is the main objective to be fulfilled via design of an integrated controller. We also proposed control strategies to manage energy consumption of the building to turn domestic heat demands into a flexible load in the smart electricity grid. Several research problems are addressed in this study that are:

- **A solution to stability/performance dilemma of TRV controlled hydronic radiators**
- **Energy minimization of a central heating system with hydronic heaters and geothermal heat pump**
- **Contribution of buildings to smart grid control**

Aspects in play

A combination of different Heating Ventilation and Air Conditioning (HVAC) subsystems might be available in a building to offer a perfect thermal comfort to the residents that directly influences their productivity and thermal satisfaction. HVAC subsystems have been regulated independently in the conventional control setups in spite of the strong cross correlation that might cause thermal dissatisfaction, performance degradation of the whole system and as a result energy inefficiency. The HVAC subsystems that condition the same space, have to work in harmony with each other and also with the specific building envelop system in order to preserve balance between energy consumption and thermal comfort. This goal is feasible via an integrated control strategy which takes into consideration all the influential dynamics and disturbances. Following aspects are believed to be of utmost importance to a central heating system. They are investigated for the specific application of the thesis i.e. a heat pump combined with hydronic floor heating and radiator panels. Please

see Fig.1. for the relevant qualitative and quantitative aspects and the tools. The objectives to be maintained by the proposed model-based multi-layer controller are as follows:

- Stable stand-alone local controllers for the system components that follow corresponding setpoints. This way, the whole control structure can be fitted to the existing commercial thermostats by only configuring interfaces to the intermediate level.
- System integration to acquire an optimal performance of the entire building system such that individual subsystems function at their optimal operating regions that depend on the thermal mass of the individual building and the weather condition. The minimized energy consumption is the result of the system optimal performance achieved by the intermediate level controller.
- Minimizing the energy cost as the immediate outcome of minimizing the energy consumption and foremost by proposing the building as a flexible load to the electricity grid. The building thermal mass is a heat buffer with a large storage potential which can contribute to the grid balancing issues based on the economic incentives that the electricity market offers to end-users.

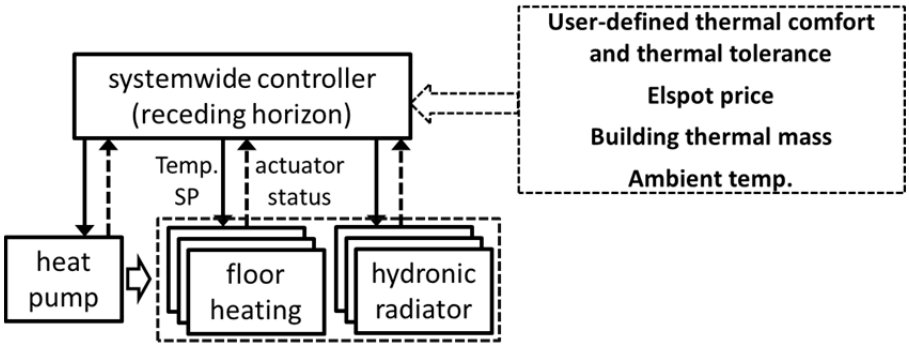

Fig.1. Hieratchical control structure

Frame of solutions

A summary of tackled problems and the proposed solutions are listed in the following.

A solution to stability/performance dilemma of TRV controlled hydronic radiators

Radiators are usually designed and regulated to meet high heat demands of the cold season. The large closed loop gain as a result of this specific design usually causes oscillations in the radiator flow and consequently in the room temperature in low heat demand seasons. The instability can be avoided by recalibration of thermostatic valves to reduce the closed loop gain, though in cost of an inferior performance during cold weather. The proposed solution is a gain scheduled controller for flow regulation instead of the conventionally used proportional (P) or proportional-integral (PI) controllers with fixed design parameters. The other influencing parameters i.e. the water temperature and pressure are centrally controlled for the entire building and can not be regulated in favor of only radiators, assuming that other HVAC systems might be available in the system. The gain scheduled controller is designed in a systematic fashion based on an analytically developed Linear Parameter Varying (LPV) model of the radiator's dissipated heat.

Energy minimization of a central heating system with hydronic heaters and geothermal heat pump

The research question of this part is: How to integrate the Ground-source Heat Pump (GHP) with the heaters to achieve optimal performance in terms of minimum energy consumption, whilst satisfying comfort constraints? The proposed hypothesis is that the optimal feed temperature happens when at least one actuator works with full capacity. The rationale behind the hypothesis is heuristic: Electricity for heating purposes is mostly consumed by the heat pump's compressor. The latter would be minimized if the heat pump's Coefficient of Performance (COP) increases. COP is inversely related to the temperature gap between condenser and evaporator sides. Minimizing this gap is doable by reducing the condenser temperature or equivalently the feed water temperature to the building. The feed temperature can be reduced to the extent that the most demanding zone of the building can still meet the corresponding thermal comfort, in other words the relevant actuator works very close to its saturation limit for example the floor heating valve is almost fully open.An optimization problem in a receding horizon scheme is formulated to seek the proposed optimal operating point.

Contribution of buildings to smart grid control

Research questions of this section are: How and to what extent, domestic heating systems can be helpful in regaining power balance in a smart grid? How much reduction in electricity bill would be achieved by load shifting based on power price? The idea is to deviate power consumption of the heat pump from its optimal value, to compensate power imbalances in the grid. Heating systems could be forced to consume energy, i.e. storing it in heat buffers when there is a power surplus in the grid; and be prevented from using power, in case of power shortage. It is shown that the large heat capacity of the concrete floor alleviates undesired temperature fluctuations. Therefore, incorporating it as an efficient heat buffer is a viable remedy for smart grid temporary imbalances. From residents' perspective, they can avoid high electricity bills by deferring their daily power consumption without loss of thermal comfort. The energy cost minimizing related publications are:

Built examples

The case study is a low energy demonstration building located in Copenhagen, Denmark. The building is built to provide test facilities for development and test of energy efficient control solutions, renewable energy sources and new facade technologies. Built in 2009, Energy Flex House (EFH) lab is an uninhabited test facility examining the interplay of various floor types, outer walls and technical installations, Fig.2.

Fig.2. Energy Flex House is a low energy building built basically for testing, developing and demonstrating innovative energy efficient solutions.

The system consists of three separate heat zones i.e. rooms. Each room has a separate grid of sub-floor PEX pipes embedded into a thick layer of concrete, in a serpentine pattern with a center-to-center distance of 100 mm. The mass flow rate through the three parallel pipe branches through individual rooms is not the same due to different hydraulic resistances. The flow is regulated by a multiple-rate circulating pump to around 32, 22 and 20 l/h through the pipes of the rooms #1,2 and 3 respectively. The average U-value of the building envelope of the reference room, including 1.6 m^2 of windows, is $0.2 W/m^2/K$. A Schematic diagram of the closed loop heating system is shown in Fig.3.

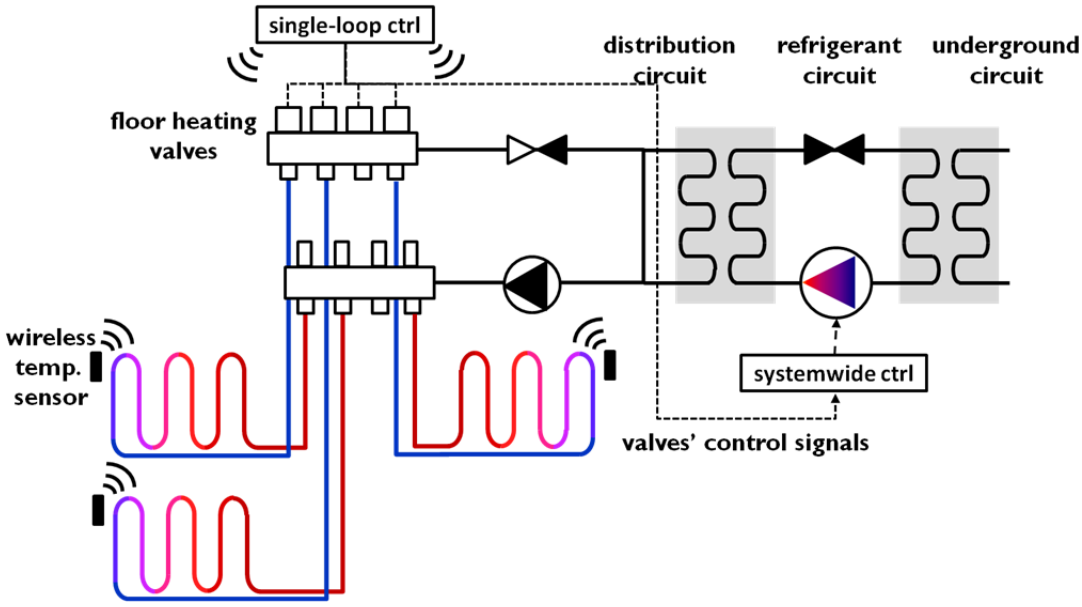

Fig.3. A schematic diagram of the piping system of Flex House (case study).

The Process

Design of the structure hast to be started has early as the engineer designs piping system for the entire house.

Tools

Simulation-based evaluation tools are toolboxes and solvers work in Matlab platform in a dynamical analysis setup.

Employed control methods i.e. *relay*, *proportional integral* and *model predictive control* are very well known and acknowledged in the control engineering world and straightforward to use. Both in simulation and actual implementation, theses controllers have been widely used and commercialized.

Economy

A cost efficient energy management is the other main concern for both electric power consumers and producers. A cut down in the electricity bill is subject to load scheduling according to power availability. The more available the power is the less expensive it would be sold by the electricity market. On the other hand, load shifting will contribute to regaining balance between power supply and demand in the grid. Continuously increasing emergence of green power, produced by renewable resources, generally makes the grid more prone to grid imbalances. Regaining balance in the grid requires that the power consumption by the storage devices e.g. electric vehicles, heat tanks and other heat/cool buffers for instance the building thermal mass can be adjusted to utilize surplus of cheap power efficiently.

To satisfy monetary interests of end users, another mechanism is devised in this section to directly affect electricity consumption based on the instantaneous price of electrical power. In this method a list of provisional price values for the coming 24 hours is communicated through the power grid by the power retailor. Such a price profile is designed in a way to encourage less consumption during peak hours by assigning a higher price. However, the task of the MPC controller at the end user is not to reduce the overall consumption which adversely affects user comfort. Instead, its job is to force the heat pump to consume energy when it is cheap and deprive it of energy consumption when the price is high.

Fig.4 illustrates how it becomes possible to decrease the consumption cost with the same average water temperature and not sacrificing thermal comfort of residents. It shows that the average water temperature is even increased 2.2% in average compared to the scenario when energy is minimized not the cost. COP is also decreased with 1.2% which is due to the increased average water temperature. However, the cost of electricity consumption is reduced by 10% in average which is subject to predicted electricity price variations shown in Fig.4. Higher fluctuations of the electricity price would lead to much more cost benefits. Also, it is worth mentioning that the comparison is performed against the minimum energy consumption results. Cost efficiency compared to the traditional methods would be much more significant.

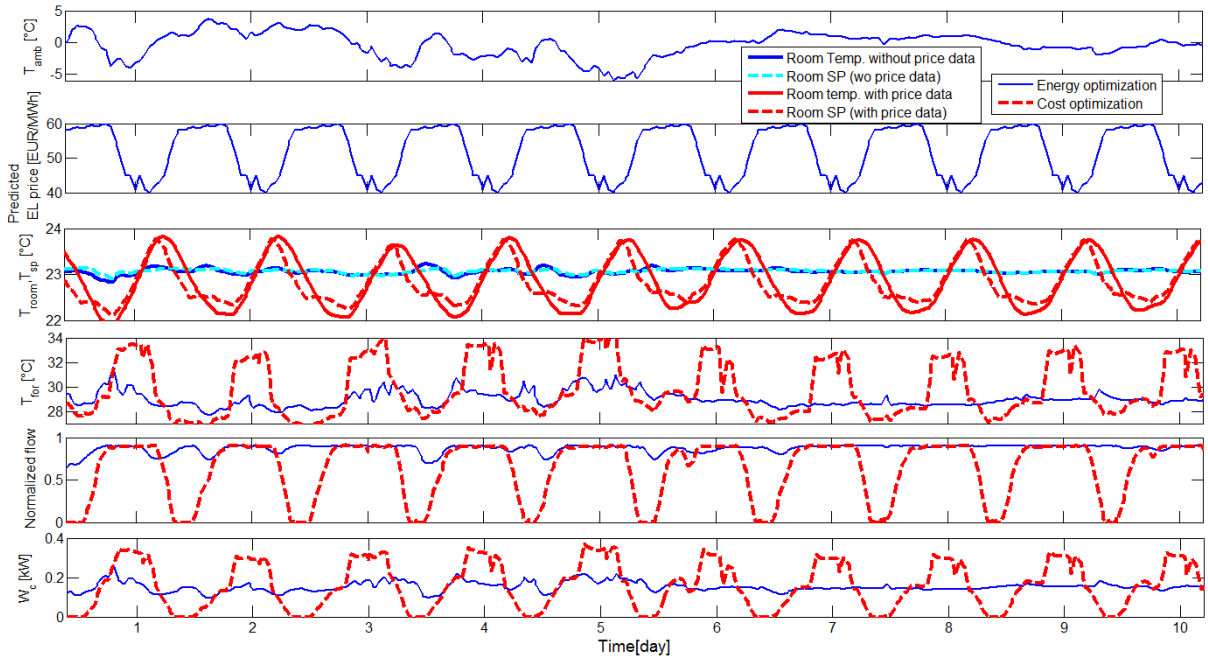

Fig. 4. Simulation results with and without price profile data

2.6

Title of PhD project: Investigation of energy flows in thermally activated building constructions

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Problem

In order to maintain comfortable conditions inside buildings, the temperature has to be controlled and two main solutions exist: the indoor climate can be maintained within a certain level by controlling the air temperature (air conditioning systems), or an alternative solution consists in controlling the surface(s) temperature through a water based system (radiant systems). These two different solutions emit or absorb heat in different ways, and will lead to different levels of comfort and energy performance. When comparing the two solutions, several advantages can be listed in favour of radiant systems:

- The level of comfort achieved by radiant solutions is usually better due to the lower air velocity. The risk of draught is greatly reduced. Moreover the environment is more uniform, as the heat is emitted (or absorbed) partly by the surfaces and partly by the air.
- The level of noise due to the fans is also largely reduced.
- Compared to conventional heating system (radiator), the activated area of a radiant system is large enough to use energy sources, which have a temperature closer to the room temperature. Radiant systems are therefore more energy efficient because they can make use of renewable energy sources such as the ground, the ground water or the outdoor air. Low temperature heating (25-40°C) and high temperature cooling (13-20°C) can be achieved.
- Radiant systems are less sensitive to the room air temperature because these systems are principally cooling down or heating up the surfaces. If the users open the windows, the energy consumption will therefore not increase as much as for air conditioning systems.
- Regarding the economical aspect, the size of the ventilation units can be decreased with radiant solutions, saving space in the building and decreasing its total height.
- Finally this type of system is integrated inside the building constructions (either mounted on a specific structure or embedded in the floor, ceiling or walls) and is therefore invisible.

Nevertheless, one should be aware of the drawbacks of radiant systems:

- As the technology is water-based and pipes are inserted inside the construction elements, there is a risk of leakage. However the probability of facing such a problem during the installation is relatively low as the technology is well known (floor heating is widely used in Denmark since the 80's). But if users are not aware of the presence of an activated system, there is a risk that they drill through the pipes.
- Over the time, the pipes could also get stacked. This phenomenon is limited if the piping system is equipped with filters.
- During the cooling season, there can be a risk of condensation at the surface of the activated element if the surface temperature is not controlled above the dew point (around 17°C). The maximum cooling capacities given in the diagram below take into consideration this parameter.
- Moreover radiant solutions can perform poorly if the level of insulation of the activated surface is low (high back losses). Nevertheless it is a minor issue as standards define the minimum level of insulation.
- Finally the activated surface should not be shaded by any object; otherwise it would decrease its efficiency.

Summary of the aspects in play

QUANTITATIVE

Achieve a desired operative temperature

Optimise the energy efficiency according to the source(s) available

Geometry of the building: size of the rooms, height of the building, raised floor or suspended ceiling

Thermal mass

Heat load / Heat losses

QUALITATIVE

Thermal comfort (e.g. draught)

Level of noise

Visibility of the heating/cooling system

Condensation

Furniture in the rooms / Flexibility of the building

MEANS

Air-based systems

Radiant systems (floor, walls or ceiling, with different possibilities in the pipes position)

Frame of solutions

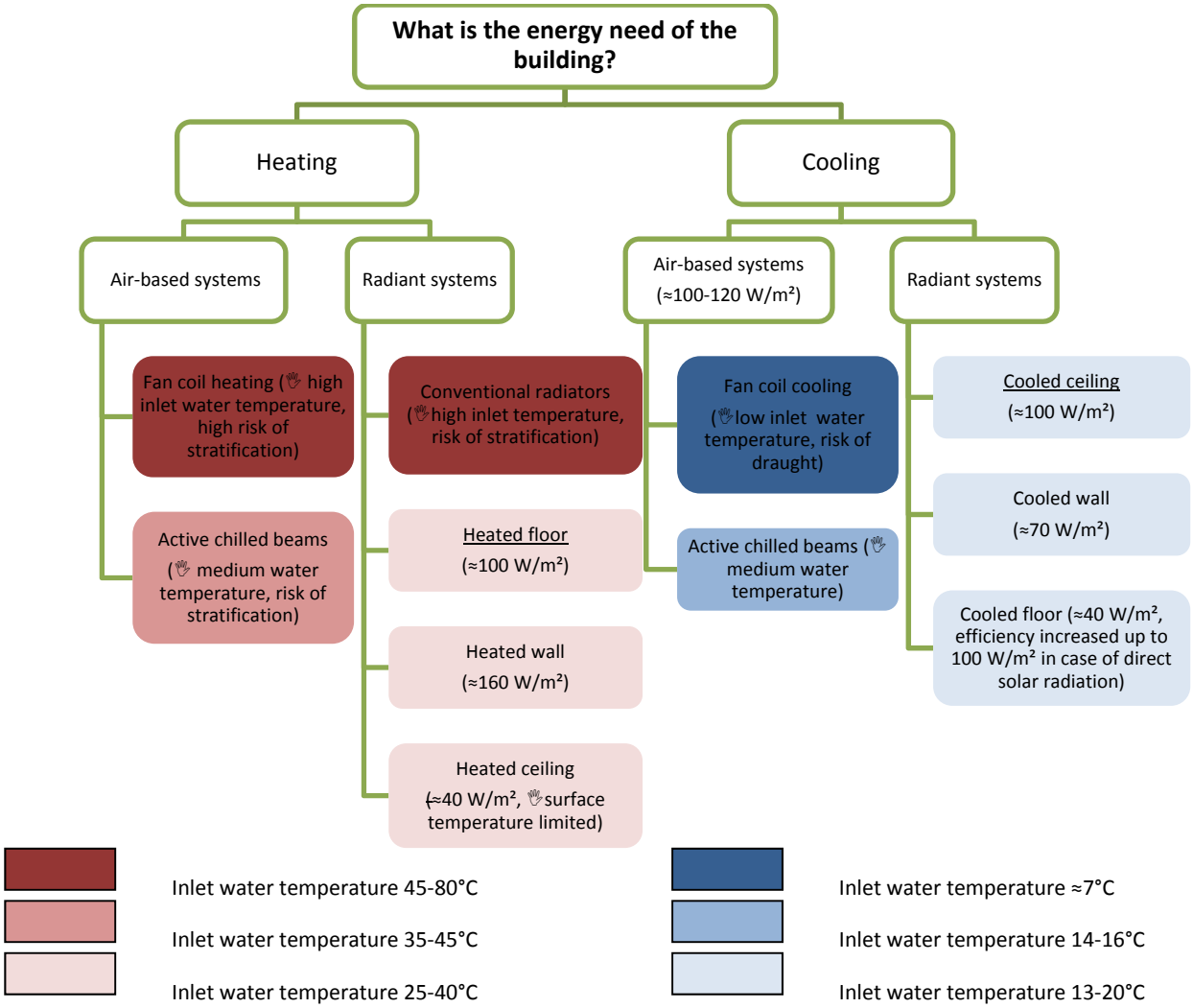

Figure 1: Selection of the type of terminal (the maximum capacity is given between parentheses and the most efficient solutions are underlined)

Radiant systems are a good solution for optimising comfort and energy consumption in Zero Energy Buildings. The most efficient solutions are obtained for surfaces that have the largest convective heat transfer coefficient, i.e. for surfaces that can more easily transfer heat to the room air.

It has to be noticed that the choice of the activated surface will not only depend on energy performance criteria. Other parameters should be taken into consideration, such as the surface availability, the geometry of the room, the type of furniture. The activated surface should be as close as possible from the occupants and free of obstacles. For example, radiant ceiling should not be applied if the room has a large floor height. If an open space is considered, radiant walls are not advised. Moreover the presence of a raised floor or a suspended ceiling has to be taken into consideration. Finally the activated surface should be as large as possible to allow the use of low temperature heating and high temperature cooling.

If a radiant solution is selected, the position of the pipes has to be defined. Two configurations, with the following characteristics, are possible:

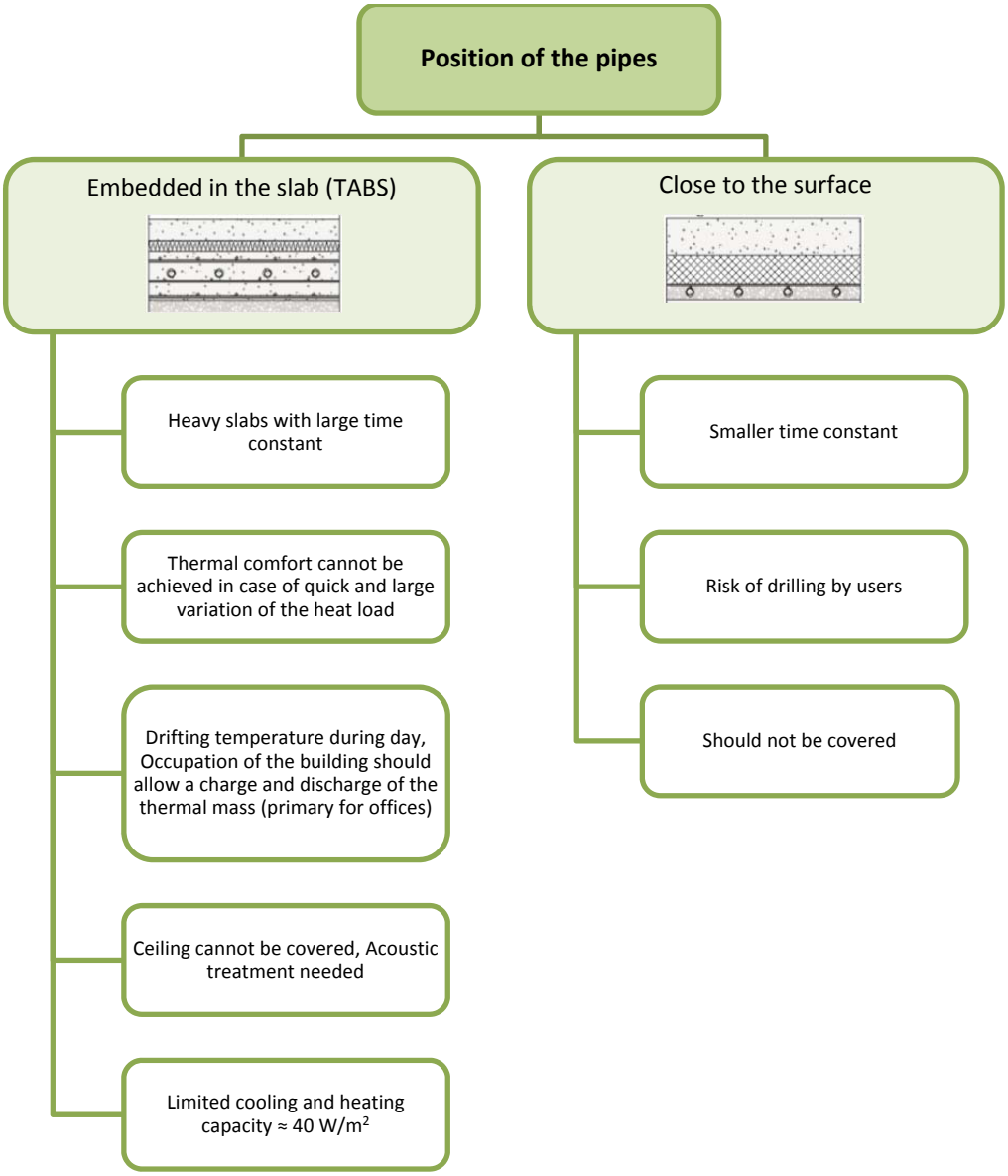

Figure 2: Selection of the pipes position (drawings from Olesen [2008])

The diameter and spacing of the pipes will vary depending on their location. Pipes with large diameter (up to 20 mm) and spacing (up to 200 mm) are used in case of Thermo-Active Building Systems (TABS), whereas pipes with small diameter (down to 3 mm) and spacing (down to 10 mm) are used for radiant panels located close to the surface.

Tools:

The technical performances of the different types of terminal are documented in different standards and most of the thermal dynamic simulation tools can simulate the two types of terminal.

Process:
The choice of the heating/cooling system should be considered as early as possible in the design process. If a radiant system is chosen, the interaction with the building structure should be taken into consideration. If an air-conditioning system is installed, the floor height might need to be increased depending on the diameter of the pipes. The energy sources available should also be considered as early as possible. Only minor changes in the type of heating/cooling system will be possible in the following stages of design.

Economy:
The cost of the different heating and cooling systems will depend on many factors: type of technology, dimensions of the building, type of heat loads, materials used for the pipes, source of energy, dimensioning of the system, etc. It is therefore difficult to generalise the cost of the different systems. But one should keep in mind that the total price does not only correspond to the initial cost, but it should also include the price of energy.

Built examples:

- For radiant systems with pipes embedded in the concrete slab:

The BOB (Balanced Office Building) is located in Aachen (Germany) and is equipped with Thermo-Activated Building Systems. In Aalborg, an office building located in the center has been equipped with TABS. In Middelfart, a bank. Projects of the architectural firm "Mejeriet".

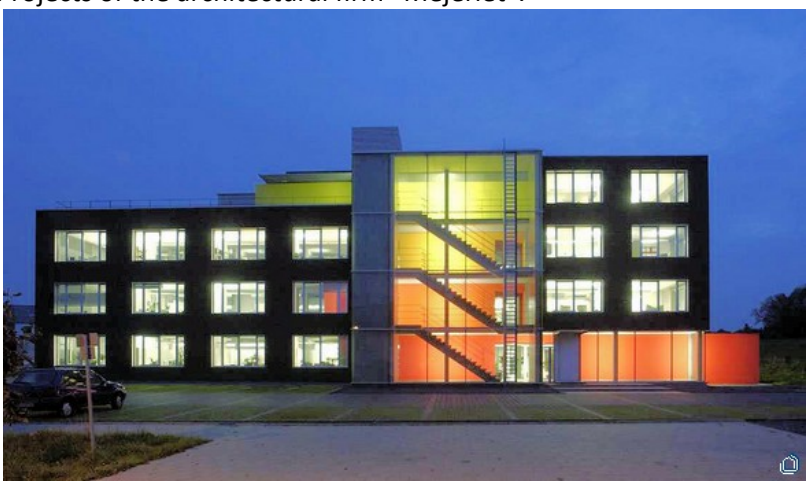

Figure 3: BOB building in Aachen (Architect: Hahn Helten - Picture: Jörg Hempel - http://www.enob.info)

Figure 4: Close-up on the pipes during the construction phase (Source: BINE Themeninfo I [2007])

- For radiant systems with pipes located close to the surface:

The State Parliament of Berlin (House of Representatives) is equipped with a cooled radiant ceiling and cooled walls. In Austria, the art museum in Bregenz is equipped of pipes embedded in the walls and in the concrete slabs. The system is used for both heating and cooling.

Figure 5: art museum in Bregenz (Architect: Peter Zumthor - Pictures: Hélène Binet - http://www.kunsthaus-bregenz.at)

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EN 1264 - 2008 - Water based surface embedded heating and cooling systems

EN 15377 - 2008 - Heating systems in buildings - Design of embedded water based surface heating and cooling systems

ISO 11855 - 2012 - Building environment design -- Design, dimensioning, installation and control of embedded radiant heating and cooling systems

2.7

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Problemstilling

In order to meet the demand for lowering the energy usage of future buildings, technologies for lowering the energy demand needs to be developed even further compared to the technologies being used today. The energy transport through the buildings external surfaces needs to be controlled in order to minimize energy demand for building services, whilst maintaining comfortable indoor climate. As the energy transport across the glazed façade is of great magnitude, the energy transport needs to be controlled here. The main factors which needs to be controlled are the following factors:

- Heat transfer
- Irradiance
- Energy storage
- Light transmittance
- Mass transport

The control of these factors results in a dynamic façade, adapting to the microclimate and the requirements inside. However the control strategy, user behavior, architectural expression, of the dynamic façade plays the dominating role with regards to energy performance and efficiency of the façade and has significant impact on the form and expression of the façade.

Aspekter i spil

Upon designing an intelligent façade factors influencing the users comfort needs to be evaluated in relation to the energy performance and architectural form of the façade. The technologies applicable (virkemidler) needs to be evaluated with regards to the performance of each individual technology (kvantitative aspekter) and needs to be correlated with the user behavior and user pattern (kvalitative aspekter) in order to optimize the performance of the intelligent façade.

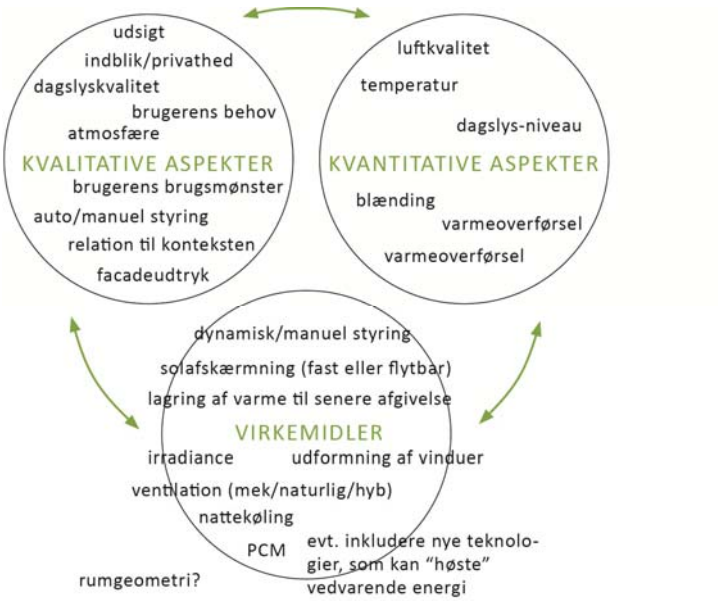

figure 1 Diagram of aspects which need evaluation.

The façade has great influence on many aspects ranging from economy, building services, human behavior, productivity, wellbeing, architectural expression, etc. and how the dynamic technologies influence each aspects can and needs to be evaluated in order to great an optimum façade design. Care should therefore be taken when choosing the technologies, and should evaluate whether the optimum solution is a dynamic solution or a static solution. As these choices have great influence on the design of the building, the decisions needs to be taken in the beginning of the design phase as the intelligent façade is part of the building shape and orientation.

Løsningsrum

The intelligent glazed façade is not one solution but involves technologies, which adapt to its surroundings. The technologies applied thus needs evaluation in relation to the use. Use of dynamic façade technologies for office buildings seems more applicable since the heat load and heat demand are significantly different during a day. The heat load is high internally during daytime hours whilst external irradiance is present and thus contributes to an increased heat load. During nighttime hours the heat load is diminished and the heat demand is highest. The heat load and heat demand of a residential building is more even. The heat load during daytime hours consists mainly of external irradiance, whilst heat load during nighttime is present due to internal load. The heat demand of the building is thus lower for residential buildings during nighttime hours.

The potential of the intelligent façade needs to be evaluated based on the use of the building and its location. Upon performing this analysis factors justifying the inclusion or exclusion of different technologies needs to be evaluated based on the qualitative and quantitative aspects, such as energy performance, economic value, environmental value, architectural expressions, and user integration. It should be noted that buildings are meant to last for 100 years whereas the intelligent façade is set to 20 years and thus involves a potential for upgrades during the building lifetime.

The dynamic façade influences many aspects and requires maintenance in order to secure the performance of the dynamic façade. This aspect increases the cost of the façade and costs relating to building servicing. However the increase in costs needs to be evaluated in relation to the savings on other aspects. For instance the increased cost on maintenance of dynamic g-value technologies needs to be compared with the savings on cooling, both with regards to running costs but also with regards to investment costs. Guidelines for the choice of façade solutions thus need to be based on the microclimate, users, and architectural expression. For more information on dynamic facades see Intelligent Glazed Facades -an experimental study.

Byggede eksempler

Built examples concerning the intelligent façade are widely used with regards to solar shading technologies. The closest façade solution, which involves dynamic u-value, dynamic g-value, natural and decentralized ventilation is shown in figure 3 and figure 5. The other figures shown below are examples of dynamic facades with equipped dynamic g-value solutions. However the examples shown are merely examples of dynamic facades and not necessarily intelligent façade solutions, since the intelligence is integrated in the control strategies.

figure 2 Kiefer Showroom, Bad Gleichenberg, Austria

figure 3 Schüco 2 grad concept, Schleswig

figure 4 Colt Nordic, Jyske Bank – Silkeborg

figure 5 Energy Frames

(giselbrecht.at & schueco.com & steffdesign.dk & www.coltinfo.dk)

Processen

In order for the intelligent glazed façade to be applicable and energy efficient in future Zero-Energy-Buildings the design of the intelligent glazed façade needs to be included in the design in the very early design phase. The evaluation of the façade in relation to the use and location of the building is necessary in order to justify the choice of the dynamic façade technologies. Relating the façade technologies to the orientation is necessary to determine the choice of the technologies. Static façade solutions can be just as energy efficient as dynamic façade technologies and thus prove more economical over the lifetime of the façade solution.

The main factors, which need determination, are the inclusion or exclusion of the following technologies:

- Dynamic or static U-value technologies
- Dynamic or static g-value technologies
- Centralized, decentralized, natural or hybrid ventilation
- Energy storage location

The first move in order to minimize energy demand for building services is to control the energy transport as much as possible whilst fulfilling the other requirements shown in figure 1. For details on the description of individual façade technologies and their influence on the energy demand for building services, see Intelligent Glazed Facades -an experimental study. Integration of building services is thus a result of the inabilities of the façade solution and needs to be designed accordingly. The building service system thus functions as a backup system when the façade solution cannot fulfill the requirements. The technical solutions, which meet the requirements, are shown below:

- Heating system
- Cooling system (ventilation system)
- Artificial lighting

Værktøjer

In order to evaluate the performance of the intelligent façade, thermal building simulation tools, energy calculation tools, etc. are used which enables the designer to sketch the potential solutions and evaluate these accordingly. Tools, which are developed presently, concern the thermal and energy performance of the intelligent façade solutions. The tools developed under Strategic Research Centre for ZEB will be included in design software used in practice under Danish building regulations and Danish Building Research Institute, SBi-BSim, SBi-BE10, Energistyrelsen & ZEB.aau.dk

Økonomi

The dynamic façade involves many technologies in comparison with traditional static facades. This implies an increase in investment cost and maintenance cost. However the maintenance costs are shifted from building service systems to the dynamic façade technologies, and can thus be considered as being of equal magnitude. Furthermore the façade must be considered a working space for service workers and thus needs to fulfill the requirements concerning safety.

Assuming the static façade costs app. DKK 3.000 pr. m² the dynamic façade can be assumed to cost between DKK 7.000-10.000 pr. m² (values based on experience). The energy savings thus needs to be of considerable magnitude and the service life needs to be of a length which makes the choice of the dynamic façade more attractive in comparison with traditional façades.

2.8

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Problem

Simplified calculation model needs to be developed to calculate the energy and comfort performance of the intelligent glazed façade in the beginning of the design stage in order to provide the potential of using the system. In addition, model also needs to be integrated into building evaluation tool to prove the performance of the intelligent façade for the building certification.

With the help of the control strategies, the intelligent glazed façade can use different technologies in a better way and provide an optimal energy and comfort performance for the buildings. Based on the simplified model of the façade, the control strategies take the outdoor weather properties, indoor comfort requirement and the characters of the buildings into account to create an optimal indoor environment with minimal energy consumption.

Aspects in play

In order to simulate the intelligent glazed façade properly, the dynamic properties of different technologies (night insulation, blind, natural ventilation) need to be modeled accurately. The angle dependence of the blind is considered in the model including both the incident angle of the solar radiation and the slat angle of the blind. Infiltration rate of the cavity between the glazing and night insulation is also taken into account. Not only the façade, but also the entire room is modeled to simulate the total energy consumption and indoor environment. The output of the model is the energy demand and the indoor comfort level.

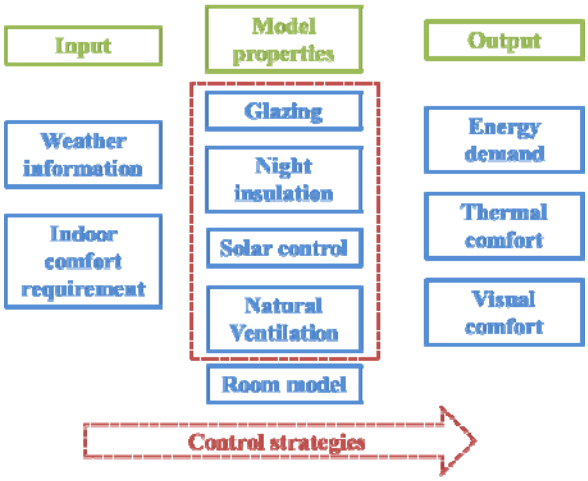


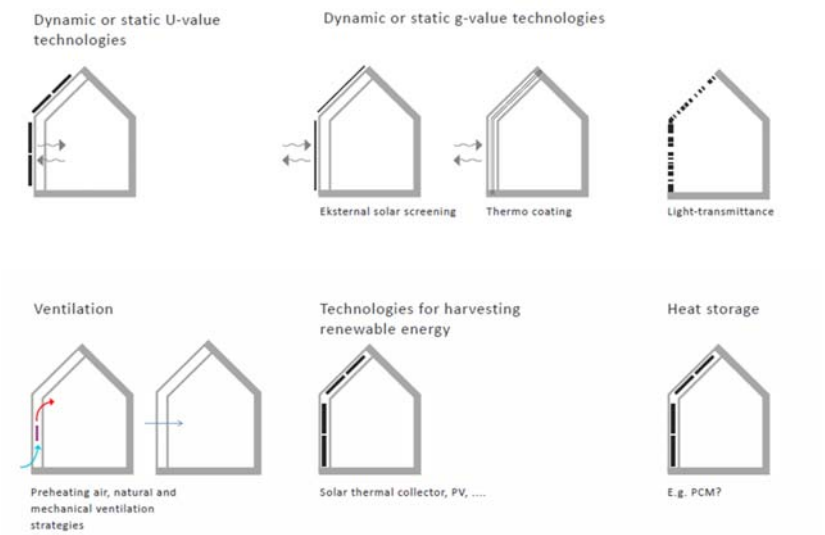
Figure 1 Diagram of aspects of the calculation method.

In order to optimize the performance of the façade with the control strategies, the properties of different technologies need to be studied in order to make use of them in the right time according to the indoor and outdoor environment, such as the temperature and the solar radiation. It also needs to be considered how to cooperate the technologies with building services (heating, cooling and lighting) to fulfill the indoor comfort level with the minimum energy demand.

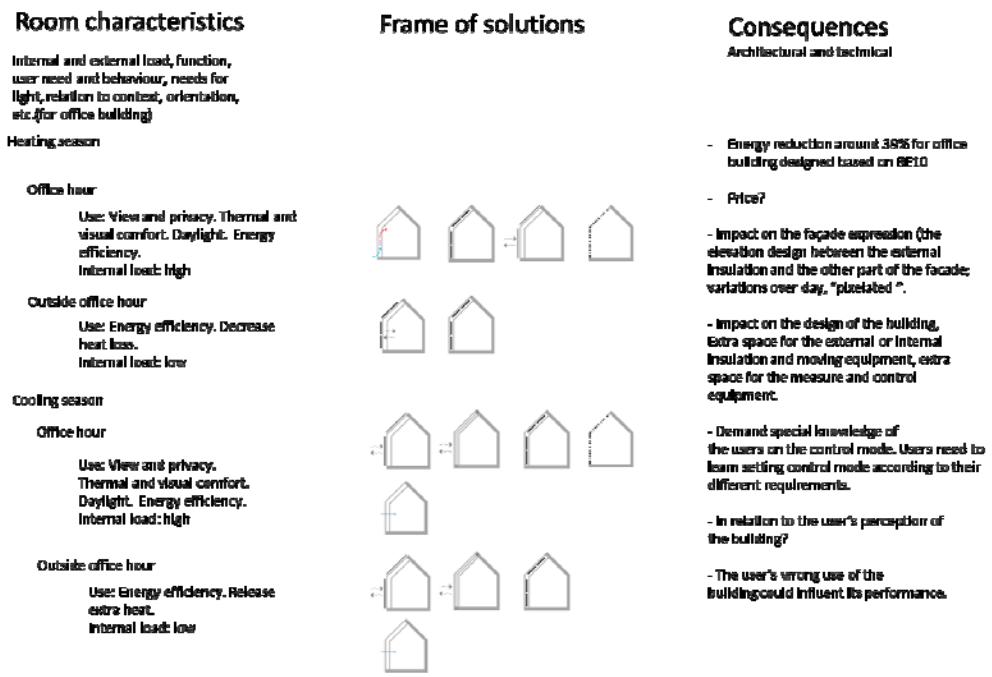
Frame of solutions

The control strategies of the intelligent façade need to be designed according to the location, orientation and climate properties, etc. of the building. In order to optimize the indoor comfort and minimize the energy demand, properties of different technologies need to be analyzed to work properly together with building services. Night insulation (dynamic U-value) can control the heat transmittance from indoor environment to outdoor. Blind (dynamic g value) can control the solar transmittance into the room. Natural ventilation can provide the air supply directly from outdoor environment to the room. These technologies can work alone or together with others to maximize the energy efficiency.

Technologies



Frame of solutions



Built examples

"Built examples concerning the intelligent façade are widely used with regards to solar shading technologies. The closest façade solution, which involves dynamic u-value, dynamic g-value, natural and decentralized ventilation is shown in Figure 2 and **Error! Reference source not found.**. The other figures shown below are examples of dynamic facades with equipped dynamic g-value solutions. However the examples shown are merely examples of dynamic facades and not necessarily intelligent façade solutions, since the intelligence is integrated in the control strategies" [3].

Figure 1 Kiefer Showroom, Bad Gleichenberg, Austria

http://pixgrove.blogspot.dk/2010/12/dynamic-facade-kiefer-technic-showroom.html

Figure 2 Schüco 2 grad concept, Schleswig

http://www.baulinks.de/webplugin/2010/1597.php4

The process

The simplified method can be used in the building simulation tool and building compliance tool in the beginning stage of the building design. The design of the intelligent glazed façade is influenced by the orientation, location and climate characteristic, etc. of the building. Therefore, it is necessary to design it in the early design phase of the building to maximize it performance. The performance of the façade needs to be simulated together with the corresponded building services. The building services are also need to be controlled related to the functions of the intelligent façade. They are active when the façade cannot fulfill the requirement of the indoor comfort.

Tools

Part of the PhD project is to develop a simplified calculation method to predict and evaluate the performance of the intelligent façade. The tools developed under Strategic Research Centre for ZEB will be included in design software used in practice under Danish building regulations and Danish Building Research Institute.

Economy

The cost of the intelligent façade needs to be investigated.

Reference

[1] M. Liu, K.B. Wittchen, P.K. Heiselberg and F.V. Winther, Development of simplified and dynamic model for double glazing unit validated with full-scale façade element, PLEA2012, 28th conference, Lima.

[2] M. Liu, K.B. Wittchen, P.K. Heiselberg and F.V. Winther, Development of a simplified and dynamic method for double glazing façade with night insulation and validated by full-scale façade element, Energy and Buildings 58 (2013) 163-171.

[3] Report by Frederik

2.9

Title of PhD project: Calculation methods for natural ventilation through centre- pivot roof windows

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A. Problem

The primary aim of building construction is to provide a healthy and comfortable indoor environment for the occupant. To achieve this aim several building services are provided to the occupants. Almost all building services i.e. heating, ventilation, air-conditioning, plumbing, lighting etc consumes energy. In Europe the building sector consumes 40% (up to 50% in Denmark [1]) of the total energy consumption [2]. In order to design buildings with low-energy approach, engineers and architects have been searching for low energy consuming devices for building services. Among all building services, ventilation serves the inhabitant of buildings to maintain healthy indoor environment.

The primary aim of ventilation of the enclosed space is to improve the indoor environment. Therefore, outside air is provided to the enclosed space and the same amount of stale air is exhausted from the space. As a consequence, internally generated airborne contaminants and odors are minimized. Depending on the outdoor air quality filtration of the supply air may be relevant. There are several other benefits of ventilation. Foremost, the airflow cools down the interior of the building by convection. The lower outdoor air temperature can also cool down the thermal mass of the building, whereby the building can remain cool for longer period, consequently decreasing indoor air temperature the following day. Ventilation during summer to cool indoor spaces can be called ventilative cooling. Conventionally a mechanical fan is used to provide the outdoor air into the occupied space. If single fan is used to provide ventilation to several occupied spaces then ducts are used to transport the outdoor air from fan outlet to the occupied spaces. The energy consumption of the fan depends upon several factors including airflow rate, type of filter, duct length, duct friction factor etc.

On the contrary, outdoor air can also flow into the occupied space and exhaust out from the occupied space by natural forces like wind velocity and thermal buoyancy – provided that there are appropriate openings in the enclosed space envelop. The ventilation of the occupied space without any assistance from fans is called natural ventilation. The effectiveness of natural ventilation i.e. its ability to ensure appropriate indoor air quality and passive cooling in buildings, depends upon design of ventilation system [3]. Natural ventilation system cannot be design in isolation with buildings. The building itself and its components can disturb the air movement and air contaminants. The effectiveness of natural ventilation is determined by the local outdoor conditions, microclimate and the building itself. The savings from natural ventilation depends upon air-change rates and construction of buildings (heavy or light), the microclimate, temperature and humidity of the outdoor air. Natural ventilation has some advantages and some disadvantages [4]. Advantages are as follows:

- In comparison with conventional mechanical ventilation system, natural ventilation utilizes zero energy as no fan power is needed
- Therefore, natural ventilation has potential savings in running cost during favorable seasons

- In conventional mechanical system the outdoor contaminants can be minimize/removed by using appropriate filters. However, duct cleaning and indoor air qualities are intimately linked [Limb 2000]. Therefore, by using portable indoor air filters or very advance electromagnetic filters in ventilation openings issues of IAQ related to duct cleaning can be resolved
- Whenever climatic conditions allow it, this mode of ventilation is very well accepted by the occupants
- Natural ventilation can reduce the cooling load. The savings depends on outdoor global and micro climate and all concerned heat loads
- Ventilative cooling can create a good indoor climate while using little or no energy
- The reduced cooling load can reduce the associated cost
- The reduced cooling load can reduce the associated CO_2 emission
- In comparison with mechanical systems, no space (for placing equipment) and no maintenance is required in natural ventilation systems
- Comparison of capital cost of natural ventilation system and mechanical ventilation systems depends upon the size of the buildings.

The following are a few disadvantages of natural ventilation system

- Designing of natural ventilation is not typical at all. The natural ventilation system needs to be designed along with the building design
- Effectiveness is dependent of outdoor conditions, shape of the building and nearby terrain
- One of the major disadvantage is the uncertainty in energy savings and ventilation performance
- Outdoor air humidity is another limiting factor for the application of natural ventilation. High humidity can cause negative impact on comfort level [Heiselberg 2006]
- It is very difficult to recover the energy loss, if required, due to natural ventilation
- At higher winds speed and lower window opening angles the noise level is high.

The knowledge of flow behavior through particular windows and other openings is the key to good design of natural ventilation systems. Unfortunately, the flow behavior through the windows and other openings are not very well known in general. However, the behavior of some façade window is known but not applied in practice. Most of the commercial software does not properly include the effect of window opening on local pressure distribution on surface. Furthermore, the flow coefficients (e.g. discharge coefficient) also depend upon the opening angle of windows. Likewise, the flow through the windows and other openings at low Reynolds number (i.e. not fully developed turbulent flows) are not exactly the same as of high Reynolds numbers. Often the flow through the window is not fully developed turbulent flow – especially during low wind speeds and higher opening angles of windows. Therefore, there is a need to investigate the effect of window opening on wind pressure coefficient. Likewise, there is a need to investigate the effect of window opening on other flow coefficients for instance discharge coefficient.

Knowledge of centre-pivot roof window

Centre-pivot roof window is the dominating roof window in residential buildings of Nordic region. The knowledge of flow calculation through the centre-pivot roof window is still vague. The calculation method of natural ventilation through this kind of window is not studied much in scientific literature. The flow through the centre-pivot roof window is mainly dependent on pressure difference across the window. Opening and closing of centre-pivot roof window influence the local roof surface pressure distribution. This project is investigating the effect on local pressure distribution by the opening of centre-pivot roof window.

The flow through the windows is traditionally calculated by the orifice flow equation. This equation involves a coefficient that relates the ideal airflow rate to the real airflow rate. This coefficient is called the discharge coefficient. The opening and closing of the centre-pivot roof window also affect the discharge coefficient. This project also investigates the discharge coefficient of centre-pivot roof windows. Therefore, the results from this project will give the knowledge of calculation procedure of airflow rate through centre-pivot roof window. Hence, the project will benefit in designing natural ventilation and consequently the nearly zero energy buildings especially in Nordic region.

B. Aspect in play

There are two major aspects that architects/engineers should consider during the designing phase of a naturally ventilated building.

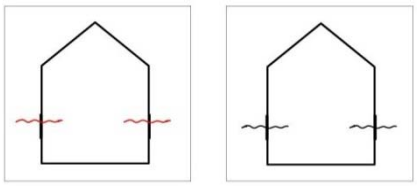
Natural Ventilation	System level	Global climate	Wind velocity, Outdoor temperature, Relative humidity
		Microclimate	Local wind velocity , outdoor temperature, outside air contaminents etc.
		Locations	Orientation of ventilation opening, location on the facade or roof
		Surface	Surface average wind pressure coefficient
		Mode of ventilation	Cross ventilation, stack ventilation or single sided ventilation
		Pressurisation	kitchen and toilets should be designed in a way that the pressure inside kitchen and toilets remain negative compared to the rest of the building
		Night cooling	Possibility of night cooling, normally intake from the bttom of the building and exhaust at the top of the building
	Componenet level	Type of Openings	Operable window or other type of openings, roof windows etc, Appropriate openings must be decided along with the decision of ventilation mode
		Airflow calculation method	e.g. if orifice equation is used then the right C_D value according to the opening area. ΔP must also be calculated according to the recommendation of window manufacturer
		Local wind pressure coefficients	Opening of window sash can disturb the pressure distributions around the window, it should be taken into account
		Glass Performance	U-value, g-values, overall energy transfer, sunlight from the window, rain protection etc should also be considered when selecting a window for ventilation
		Controls	controlling of opening and closing window (automatic or manual) can be decided according to the usage and location of window. However, for proper ventilation system automatic controls is advisble
		Security	There is a security risk in opening of window especially during night hours.

C. Frame of solution

Three major natural ventilation approaches are:

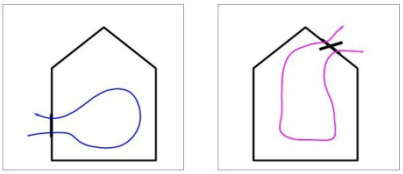
- Cross ventilation – this mode of natural ventilation occur through the openings in the opposite side of the building. Cross ventilation can occur due to wind effect and it can also occur due to the combined effect of thermal and wind.
- Stack ventilation – the dominating cause is the thermal buoyancy in this mode of natural ventilation. Ventilation relies on buoyant effect i.e. lighter warm air move upward in the space. Therefore, the ventilation occurs through the opening at different heights. The inflows are from the openings at lower portion of occupied space and outflows/exhausts are from the openings at the top or upper part of the space.

Single sided ventilation – typically this mode of natural ventilation occur through the single opening therefore it provides ventilation solutions for single room. The cause of this mode of ventilation can be wind, buoyant effect or the combination of all effects.



Cross ventilation

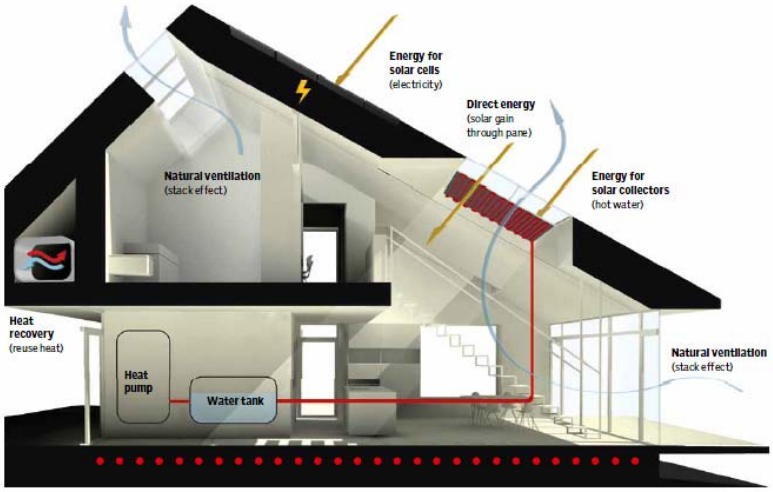
Stack ventilation

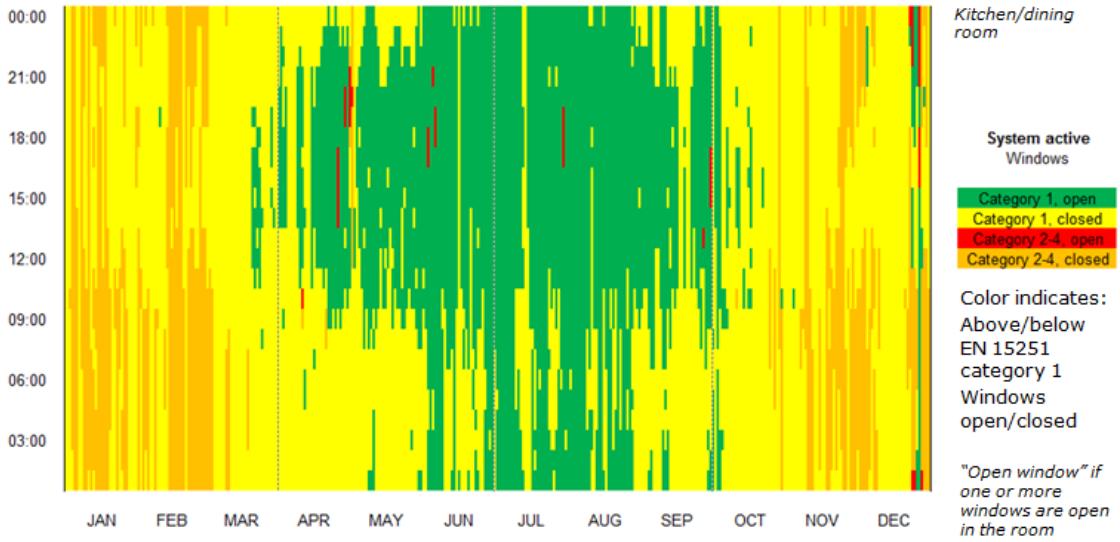


Single sided ventilation

D. Built examples

Almost all residential houses have natural ventilation system (through windows and doors). However, following is an example where natural ventilation is considered in the building design from the start. VELUX has built six model homes 2020 throughout Europe following the active house principal, where the built houses have low energy consumption while having optimal conditions for daylight and fresh air. The Model homes 2020 have proven that by using natural ventilation through ventilative cooling during summer a good thermal comfort can be achieved with low energy consumption. In the model home, Home for life/Bolig for livet (courtesy VELUX A/S) the thermal comfort has been evaluated and have overall shown satisfactory results. The good performance is achieved with automatic control of window openings and solar shading, where especially the ventilative cooling from open windows was important. The use of window openings in the summer time generally occurred at the same time as category I thermal comfort, indicating that ventilative cooling contributed to good thermal comfort as seen in the temporal map below showing thermal comfort categories according to the hour and month [Strategies for controlling thermal comfort in a danish low energy building, Peter Foldbjerg, 2011].


Energy for solar cells (electricity)
Direct energy (solar gain through pane)
Natural ventilation (stack effect)
Energy for solar collectors (hot water)
Heat recovery (reuse heat)
Heat pump
Water tank
Natural ventilation (stack effect)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JUL
AUG
SEP
OCT
NOV
DEC
Kitchen/dining room
System active
Windows
Category 1, open
Category 1, closed
Category 2-4, open
Category 2-4, closed
Color indicates: Above/below EN 15251 category 1 Windows open/closed
"Open window" if one or more windows are open in the room

E. The process

Natural ventilation system needs to be design together with the building design. It is due to the fact that building and its components (e.g. windows) strongly influences the airflow rate and the airflow patterns. Likewise, the transfer of airborne contaminants can also be minimizing if the system is design along with the building design. Architects and engineers need to acquire the adequate knowledge about building characteristics, ventilation component characteristics, the natural ventilation system and their interactions in order to design a building with a passive low energy approach [4].

F. Tools

Commonly used tools in practice are: BSim, CONTAM, loopDA , CFD, IDA ICE, etc.

G. Economy

Windows are always a part of buildings. This technology is all about using them efficiently. By using windows in buildings passive solar energy can enter the building to reduce heating energy and can during summer by openable windows reduce cooling energy, thereby saving both energy and money.

References:

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3. Modeling of natural and hybrid ventilation, *Per Heiselberg*, 2006
4. Design of natural and hybrid ventilation, *Per Heiselberg*, 2006
5. Barriers to natural ventilation design of office buildings, *National report Sweden*,1998