CITIES
Centre for IT Intelligent Energy Systems

Control of heat pumps

Objective

The objective of this CITIES demonstration project is to implement, test and demonstrate a fluid-borne heating system with a heat pump and a solar collector in a domestic building that makes optimal use of renewable energy from the grid. This implies a test of model predictive control technologies that are able to benefit from probabilistic forecasts of heat load and energy prices. The controllers must be able to benefit from energy forecast services.

Partners

- Grundfos
- DTU Compute
- Enfor

Background

Buildings are responsible for 40% of the global energy consumption. In energy systems with a large integration of fluctuating renewable sources, maintaining the instantaneous balance between energy production and consumption is a challenge. Domestic buildings can contribute to ensuring this balance either by exploiting the inertia in their thermal mass or through the installation of storage tanks. Indeed, both options imply a certain flexibility as to when electricity should be consumed for heating purposes. The optimal use of this flexibility requires forecasts of heat loads as well as of electricity prices, and smart appliances that are able to exploit these forecasts and turn them into control actions.

Connection with CITIES WP's

- WP1: User behavior, load profiles
- WP3: Models for heat dynamics of buildings
- WP5: Forecasts of electricity prices and load, methodologies for model predictive control.

Description

The building is a typical Danish family house. The house is divided in three floors:

- **the basement** is equipped with a *state-of-the-art* heating system,
- **first and second floor** are two separate flats, which are used by two tenants. Each flat has a living room (stue), a kitchen and a bedroom. The bathrooms are located at the ground floor and are not shared.

The basement houses all the hardware as well as a room, which is used as an office for the researchers. The heating system is based on radiators, exception made for the bathrooms and the basement, which are equipped with floor heating.

Heat is provided from different sources: a heat pump, a solar collector and the district heating network. The heat pump has a 300 meters ground pipe, while the solar thermal collector used to collect hot water is 7.2 m^2 wide. A stratified hot water tank with a capacity of 600 litres is used as a buffer to store heat. A domestic hot water module provides and monitors water sources to the house. The system is highly flexible and can be configured by excluding or including different heat sources. The heating system can be controlled with optimal controllers designed by the researchers. Plans for the floors and the heating system are available.

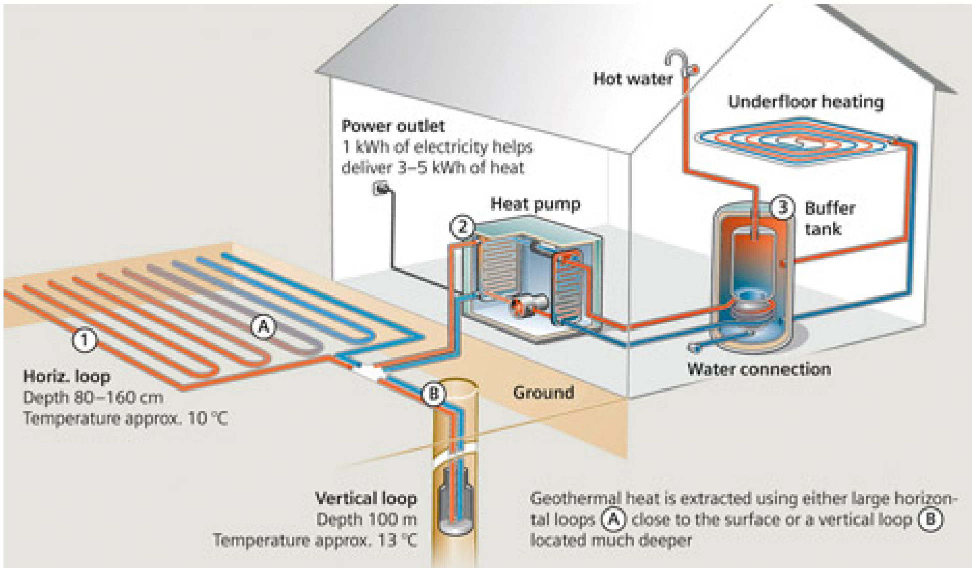
The only external set-point available to the researchers, at this moment, is the water temperature on the send, out of the heat pump supply. The delivery request is handled, internally, by a Grundfos controller which controls the heat pump. The Solar Collector is provided of a pump which cannot be externally controlled at the moment. The controller is equipped with a Simulink Real-Time target. xPC Target enable the execution of Simulink models on a target computer for hardware-in-the-loop (HIL) simulation, rapid control prototyping, and other real-time testing applications. It provides a library of drivers, a real-time kernel, and a host-target interface for real-time monitoring, parameter tuning, and data logging.

Available data

Temperature sensors are used to monitor different temperatures in the hot water tank, rooms, floors, water in the pipes, ambient and solar thermal collector. Seven energy meters provide information such as flow, send and return water temperatures and energy consumption in high resolution (minutes).

A MET station is placed outside the house to measure ambient temperature, humidity, wind chill, wind speed, wind direction, rain rate, solar radiation, UVs, solar energy and solar radiation.

Methodology



Stochastic grey box models for the heat dynamics in a building

Real-life data of energy consumption in buildings, like those obtained by using smart meters, reflects a dynamic situation, since the ambient air temperature, solar radiation, etc. vary. Hence, these real-life time-series can provide meaningful and rather accurate information about the thermal characteristics of buildings. The prerequisite for obtaining reliable, accurate and detailed information based on dynamic testing or time series data is that proper statistical methods are implemented.

Traditionally, thermal modelling of buildings is done using simulation tools which take information about the construction, weather data, occupancy etc. as inputs and generate deterministic energy profiles of the buildings. This approach often fails in predicting the actual heat consumption of buildings once they are constructed because of the lack of adaptivity.

In order to describe the heat transfer for modern buildings it is important to be able to model nonlinear phenomena like the heat transfer by radiation, wind speed driven convection, etc. Non-linearities and non-stationarities are most conveniently modelled by considering continuous-time stochastic models.

The final model structure will be established using statistical grey-box methods, and the parameters of the embedded model will be found using estimation techniques. The model will be formulated as a stochastic state-space model in continuous time, e.g. dynamics will be described as a set of stochastic differential equations.

This approach bridges the gap between physical and statistical modelling. Hence, the final model is most often called a grey-box model. This approach is attractive from a modelling viewpoint since the parameters of such models may be directly translated to physical characteristics. Interactions between floors will be studied to provide a better description of the dynamics inside the building.

Grey-box modelling gives a representation of the physical structure of the building developing a physical model and selects the most important parameters representing the aggregated physical model statistically. This approach has great potential for fault detection and support diagnosis. Applying grey-box models is well proven as a comprehensive and accurate method to obtain knowledge of the thermal properties of a building. It is applicable to the project due to the high quality and quantity of data expected from the buildings. This work can be considered as going beyond the state of the art as there are few examples of the integration of these two optimization methodologies within retrofitting projects. A good example of that is the interactive service developed within the Danish project “My E-Home” (minbolig.elsparefonden.dk, ENFOR, 2008). This is not a full integration within a Building Management System (BMS) but offers a good example of the potential of these methods.

Statistical models for user behaviour

Occupancy modelling is a necessary step towards reliable simulation of energy consumption in buildings. As buildings get more energy-efficient, internal loads and user behavior increasingly influence the energy consumption. The heat input provided by the presence of people, the devices and systems they use is becoming an increasingly important signal to model. Most simulation tools use deterministic occupancy profiles to simulate internal loads. However, such occupancy patterns will largely depend on the specific use of the building, and hence the profiles must be empirically based.

A probabilistic method for modelling the time dependence and the dynamics of presence of occupants will be developed and applied by estimation and model validation on the data from this building. The approach to modelling occupants presence will provide a flexible method that could be used in different simulation tools.

The method will include modelling of dependence on time of day, and will be able to capture per-student sequence dynamics.

This case study will serve as an important example allowing to user behavior in a traditional Danish house environment. The outcome is techniques for an occupancy simulation model that can be used in programs to simulate and control demand responsive systems.

The specific target of this task is to develop common definitions of occupant behaviour (OB), to establish simulation methodologies to model OB, and to set the basis for a further integration of these OB models with the controller. Specific objectives in relation to occupant behaviour are summarised below:

- To identify quantitative description and classification of occupant behaviour taking into the account the requirements of the pilot site building.
- To develop the necessary algorithms to model the OB for residential buildings. Several types of OB models will be analyzed, ranging from simple deterministic models, to the more complex stochastic ones. The complexity of the OB models will depend on the level of detail of the occupancy monitoring data gathered in each pilot sites, e.g., if occupants cannot influence the performance indicator, the lowest resolution model will be selected.

Predictive controllers

These methods allow for the integration of flexible thermal loads in a smart energy system in which consumption follows the fluctuating production.

Predictive controllers are usually employed because they allow for optimization over a time horizon using a forecast of the possible variability of exogenous events such as weather, demand and prices. Model Predictive Control (MPC) is widely studied in the Smart Grid literature as a control framework for demand response.

Integrating predictions in the controller improves performance significantly as the controller can react to future disturbances ahead of time. Weather conditions affect the flexibility of distributed energy resources, like buildings with flexible heating. Furthermore, the stochastic nature of renewable energy production from wind and solar is an important factor to be taken into account.

The basic principle of MPC is to optimize a sequence of control moves over a finite prediction horizon. The total power consumption of all loads is controlled indirectly through an external signal (e.g. price). The MPC incorporates forecasts of the power production and disturbances that influence the loads, e.g., time-varying weather forecasts, in order to react ahead of time.

Forecast services for control

Forecast services are crucial for optimal decision-making, production planning, trading of power and for control. In this section we briefly describe the list of forecast services needed, discuss the statistical forecast characteristics, and illustrate how the forecasts can be used in optimal control and decision making.

It is clear that forecasts are needed both on a day-to-day basis, e.g., in order to provide input for the market clearing, and for the optimal production planning, as well as on a shorter horizon, e.g. in order to use the flexibility of the distributed energy resources to control the electricity load.

The predictive controllers considered are based on forecasts of load, prices, etc. The forecast services needed depend on whether Direct Control (DC) or Indirect Control (IC, also referred to as or control-by-price) is implemented:

- Load (demand or flexibility) forecasts (for both DC and IC)
- Price forecasts (only for IC)
- State forecasts (e.g. room temperature) (only for DC)

In all cases it is assumed the appropriate meteorological forecasts are available.

Deliverables

- Setup in a typical family house (Grundfos)
- Forecasts services for control of heat pumps (Enfor)
- Predictive controllers for heat pump (DTU Compute)
- Energy management controller (Grundfos)
- Report on methods for calibrating physical building performance simulation models
- Data-driven models for occupancy behaviour modelling

Time schedule

January 2015 to April 2016