Estimating the influence of rebound effects on the energy-saving potential in building stocks

The energy-saving potential in buildings (e.g. buildings proposed for an energy upgrade in an energy policy context) is often overestimated because implicit factors, such as rebound effects, are ignored. In order to get an accurate estimate of the realisable energy-saving potential in a building stock, these factors, as well as how they differ among buildings with different characteristics, must be accounted for. On the building stock level, detailed information about the actual conditions in each building (e.g. indoor temperatures, domestic hot water consumption, internal heat loads, etc.) is rarely available. In its place, fixed assumptions are often made, usually disregarding the characteristics of the buildings. Therefore, a method that is based on available building stock data is needed for adjusting this technical energy-saving potential. This study investigated how the heat consumption in residential buildings might be expected to change due to an energy upgrade, using a hybrid bottom-up model of the Danish residential building stock. Pseudo-rebound effects, inherent to the thermal standard of the building, were quantified in a sample of 134,000 buildings with different characteristics. Results showed that estimating the heat-saving potential on the basis of the thermal characteristics alone (i.e. the technical heat-saving potential), would lead to a considerable overestimation of the realisable heat-saving potential in the residential building stock. However, the size of the realisable heat-saving potential was found to vary considerably among buildings with different characteristics, despite having the same technical potential. This indicated that the technical heat-saving potential should be corrected differently in buildings with different characteristics.
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4.64 SJR 2.055 SNIP 1.968
Web of Science (2016): Impact factor 4.067
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.07 SJR 2.04 SNIP 2.146
Web of Science (2015): Impact factor 2.973
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.21 SJR 2.079 SNIP 2.875
Web of Science (2014): Impact factor 2.884
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.79 SJR 1.852 SNIP 2.404
Web of Science (2013): Impact factor 2.465
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.36 SJR 1.745 SNIP 2.696
Web of Science (2012): Impact factor 2.679
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 3.23 SJR 1.476 SNIP 2.531
Web of Science (2011): Impact factor 2.386
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.626 SNIP 2.08
Web of Science (2010): Impact factor 2.046
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.533 SNIP 1.811
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.681 SNIP 2.055
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.077 SNIP 1.702
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.382 SNIP 1.764
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 1.292 SNIP 1.352
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.854 SNIP 1.674
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 1.504 SNIP 1.387
Scopus rating (2002): SJR 1.189 SNIP 1.671
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 0.972 SNIP 1.082
Scopus rating (2000): SJR 0.243 SNIP 1.235
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 0.241 SNIP 0.669
Semi-dispatchable generation with wind-photovoltaic-fuel cell hybrid system to mitigate frequency disturbance

Variability of large-scale wind and solar energies as power sources creates a disadvantage and a challenge for frequency control in distribution networks. In this work, an Advanced Energy Management System (AEMS) for a hybrid generation system is proposed. The AEMS is based on tracking the load curve or final user's required power to be supplied by a model predictive control design. The aim of the presented method is to propose an energy management system for massive integration of hybrid systems as distributed generation without influencing the network frequency. The main advantage of the proposed approach is to overcome the influence of frequency instability, using forecast and predictive control. The designed method uses probabilistic information for short-term wind and photovoltaic power generation as an input of the management system; hence the outcome of the hybrid system is the power demanded by the store. A case study displaying the performance of the AEMS developed is presented. Historical data of wind speeds, solar radiation and load profiles are used to control the output power generated by a hybrid system. The proposed energy management approach provides the liberty to manipulate the output power of the hybrid system considering the system boundaries without disturbing the network frequency.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Universidad Nacional Autonoma de Mexico
Contributors: Alvarez-Mendoza, F., Angeles-Camacho, C., Bacher, P., Madsen, H.
Pages: 60-67
Publication date: 1 Dec 2018
Peer-reviewed: Yes

Publication information
Journal: Electric Power Systems Research
Volume: 165
ISSN (Print): 0378-7796
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.31 SJR 1.048 SNIP 1.412
Web of Science (2017): Impact factor 2.856
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.32 SJR 1.032 SNIP 1.516
Web of Science (2016): Impact factor 2.688
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 2.74 SJR 0.962 SNIP 1.606
Web of Science (2015): Impact factor 1.809
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 2.86 SJR 0.996 SNIP 1.867
Web of Science (2014): Impact factor 1.749
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 2.92 SJR 1.061 SNIP 1.902
Web of Science (2013): Impact factor 1.595
A cross-disciplinary path to healthy and energy efficient buildings

This paper complements existing Smart City taxonomies with a case study of concrete cross-boundary collaboration between actors from diverse disciplines and institutions. The paper explores technical, social and organizational aspects of indoor climate in public buildings in Copenhagen, and outlines a digital platform (skoleklima.dk/climify.org) for the visualization and evaluation of locally produced data. The platform is to improve temporarily challenging situations ‘right-in-time’, help to solve continuous problematic conditions in the buildings and provide a scientific data infrastructure for better political decision-making. Furthermore, the paper suggests that research in active public organizations (‘living labs’) unfolds in erratic and dynamic trajectories, and in order to attain comprehensive understanding and reach innovative solutions, involved actors need to explore and intertwine diverse technical, social, political and organizational circumstances. With an empirically outset, the paper thus opens for new contextual driven understandings of cross-boundary collaboration in Smart City development.
Probabilistic forecast algorithms for grid control D82.3

General information
State: Published
Organisations: Dynamical Systems, Department of Applied Mathematics and Computer Science, National and Kapodistrian University of Athens, Laboratorio Nacional de Energia e Geologia, Instituto National de Engenharia e Tecnologia Industrial, University of Athens
Number of pages: 114
Publication date: 2018

Bibliographical note
IRPWIND 609795, This is an internal report and therefore not available in full text. Please contact author’s or director of author’s department for further information
Research output: Research – Report – Annual report year: 2018

Online short-term forecast of greenhouse heat load using a weather forecast service

In some district heating systems, greenhouses represent a significant share of the total load, and can lead to operational challenges. Short term load forecast of such consumers has a strong potential to contribute to the improvement of the overall system efficiency. This work investigates the performance of recursive least squares for predicting the heat load of individual greenhouses in an online manner. Predictor inputs (weekly curves terms and weather forecast inputs) are selected in an automated manner using a forward selection approach. Historical load measurements from 5 Danish greenhouses with different operational characteristics were used, together with weather measurements and a weather forecast service. It was found that these predictors of reduced complexity and computational load performed well at capturing recurring load profiles, but not fast frequency random changes. Overall, the root mean square error of the prediction was within 8–20% of the peak load for the set of consumers over the 8 months period considered.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Aalborg University
Contributors: Vogler-Finck, P. J., Bacher, P., Madsen, H.
Pages: 1298-1310
Publication date: 1 Nov 2017
Peer-reviewed: Yes

Publication information
Journal: Applied Energy
Volume: 205
ISSN (Print): 0306-2619
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 8.44 SJR 3.162 SNIP 2.765
Web of Science (2017): Impact factor 7.9
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 7.78 SJR 3.011 SNIP 2.61
Web of Science (2016): Impact factor 7.182
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 6.4 SJR 2.835 SNIP 2.593
Web of Science (2015): Impact factor 5.746
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 6.93 SJR 3.158 SNIP 3.218
Web of Science (2014): Impact factor 5.613
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 6.59 SJR 3.06 SNIP 3.346
Web of Science (2013): Impact factor 5.261
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 5.69 SJR 2.778 SNIP 3.076
Web of Science (2012): Impact factor 4.781
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 5.5 SJR 2.416 SNIP 2.827
Web of Science (2011): Impact factor 5.106
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.531 SNIP 2.259
Web of Science (2010): Impact factor 3.915
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.992 SNIP 1.85
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 0.95 SNIP 1.206
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.168 SNIP 1.704
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.95 SNIP 1.277
Scopus rating (2005): SJR 1.02 SNIP 0.988
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.67 SNIP 0.844
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 0.713 SNIP 0.775
Scopus rating (2002): SJR 0.589 SNIP 0.779
Determination of thermal characteristics of standard and improved hollow concrete blocks using different measurement techniques

The lighter weight, improved thermal properties and better acoustic insulation of hollow-core concrete blocks are few of the characteristics that one encounters when comparing them to traditional Maltese globigerina limestone solid blocks. As a result, hollow concrete blocks have recently been in greater demand. However, their transmittance, or $U$-value, is still quite high and does not meet the minimum energy requirements for constructing new buildings. This paper is focused on the investigation of the thermal properties of a new building block, developed as part of a nationally-funded research project ThermHCB, with the aim of improving the $U$-value of such blocks without changing their compressive strength, physical dimensions or manufacturing process. Measurement techniques were applied to obtain comparative values of the thermal transmittance for standard and improved HCBs, using different EN and draft standards. Compressive testing was carried out concurrently in order to ensure that the minimum benchmark compressive strength was reached. The comparison between these results provides information on the reliability of the methodologies used to determine the thermal properties of building elements in-situ, without having to conduct such tests in a laboratory hot box setup.

Multi-site solar power forecasting using gradient boosted regression trees

The challenges to optimally utilize weather dependent renewable energy sources call for powerful tools for forecasting. This paper presents a non-parametric machine learning approach used for multi-site prediction of solar power generation on a forecast horizon of one to six hours. Historical power generation and relevant meteorological variables related to 42 individual PV rooftop installations are used to train a gradient boosted regression tree (GBRT) model. When compared to single-site linear autoregressive and variations of GBRT models the multi-site model shows competitive results in terms of root mean squared error on all forecast horizons. The predictive performance and the simplicity of the model setup make the boosted tree model a simple and attractive compliment to conventional forecasting techniques. (C) 2017 Elsevier Ltd. All rights reserved.
Several studies have shown that the actual thermal performance of buildings after construction may deviate significantly from its performance anticipated at design stage. As a result, there is growing interest in on site testing as a means to assess real performance. The IEA EBC Annex 58-project ‘Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements’ focused on on site testing and dynamic data analysis methods that can be used to characterise the actual thermal performance and energy efficiency of building components and whole buildings. The research within this project was driven by case studies. The current paper describes one of them: the thermal characterisation of a round robin test box. This test box can be seen as a scale model of a building, and was built by one of the participants. During the project, its fabric properties remained unknown to all other participants. Full scale measurements have been performed on the test box in different countries under real climatic conditions. The obtained dynamic data has been distributed to all participants who had to characterise the thermal performance of the test box’s fabric based on the provided data. The paper compares the result of different techniques, ranging from a simple quasi-stationary analysis to advanced dynamic data analysis methods, which can be used to characterise the thermal performance based on on-site collected data.

**On site characterisation of the overall heat loss coefficient: comparison of different assessment methods by a blind validation exercise on a round robin test box**

Several studies have shown that the actual thermal performance of buildings after construction may deviate significantly from its performance anticipated at design stage. As a result, there is growing interest in on site testing as a means to assess real performance. The IEA EBC Annex 58-project ‘Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements’ focused on on site testing and dynamic data analysis methods that can be used to characterise the actual thermal performance and energy efficiency of building components and whole buildings. The research within this project was driven by case studies. The current paper describes one of them: the thermal characterisation of a round robin test box. This test box can be seen as a scale model of a building, and was built by one of the participants. During the project, its fabric properties remained unknown to all other participants. Full scale measurements have been performed on the test box in different countries under real climatic conditions. The obtained dynamic data has been distributed to all participants who had to characterise the thermal performance of the test box’s fabric based on the provided data. The paper compares the result of different techniques, ranging from a simple quasi-stationary analysis to advanced dynamic data analysis methods, which can be used to characterise the thermal performance based on on-site collected data.

**General information**

State: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, KU Leuven, CIEMAT
Contributors: Roels, S., Bacher, P., Bauwens, G., Castaño, S., Jiménez, M. J., Madsen, H.
Pages: 179-189
Publication date: 2017
Peer-reviewed: Yes

**Publication information**

Journal: Energy and Buildings
Volume: 153
ISSN (Print): 0378-7788
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Stochastic model of wind-fuel cell for a semi-dispatchable power generation

Hybrid systems are implemented to improve the efficiency of individual generation technologies by complementing each other. Intermittence is a challenge to overcome especially for renewable energy sources for electric generation, as in the case of wind power. This paper proposes a hybrid system as an approach for reducing and overcoming the volatility of wind power, by implementing storage technology, forecasts and predictive control. The proposed hybrid system, which is suitable for the distributed generation level, consists of a wind generator, an electrolyzer, hydrogen storage and a polymer electrolyte membrane fuel cell, which are embedded in one complete system with the wind power. This study uses historic wind speed data from Mexico; the forecasts are obtained using the recursive least square algorithm with a forgetting factor. The proposed approach provides probabilistic information for short-term wind power generation and electric generation as the outcome of the hybrid system. A method for a semi-dispatchable electric generation based on time series analysis is presented, and the implementation of wind power and polymer electrolyte membrane fuel cell models controlled by a model predictive control approach is developed.
Load forecasting of supermarket refrigeration

This paper presents a novel study of models for forecasting the electrical load for supermarket refrigeration. The data used for building the models consists of load measurements, local climate measurements and weather forecasts. The load measurements are from a supermarket located in a village in Denmark. Every hour the hourly electrical load for refrigeration is forecasted for the following 42 h. The forecast models are adaptive linear time series models. The model has two regimes; one for opening hours and one for closing hours, this is modeled by a regime switching model and two different methods for predicting the regimes are tested. The dynamic relation between the weather and the load is modeled by simple transfer functions and the non-linearities are described using spline functions. The results are thoroughly evaluated and it is shown that the spline functions are suitable for handling the non-linear relations and that after applying an auto-regressive noise model the one-step ahead residuals do not contain further significant information.
Non-parametric method for separating domestic hot water heating spikes and space heating

In this paper a method for separating spikes from a noisy data series, where the data change and evolve over time, is presented. The method is applied on measurements of the total heat load for a single family house. It relies on the fact that the domestic hot water heating is a process generating short-lived spikes in the time series, while the space heating changes in slower patterns during the day dependent on the climate and user behavior. The challenge is to separate the domestic hot water heating spikes from the space heating without affecting the natural noise in the space heating measurements. The assumption behind the developed method is that the space heating can be estimated by a non-parametric kernel smoother, such that every value significantly above this kernel smoother estimate is identified as a domestic hot water heating spike. First, it is showed how a basic kernel smoothing approach is too simple to deliver reliable results. Therefore the problem is generalized to a local least squares problem, which makes it possible to design a robust kernel smoother, which estimate is not affected by the spikes. Furthermore, the generalized model makes it possible to estimate higher order local polynomials. Finally, the results are evaluated and it is found that the method is capable of calculating a reliable separation of the total heat load into the two components.

The Smart-Energy Operating-System (SE-OS) framework has been developed within the CITIES research project (www.smart-cities-centre.org). This framework enables a systematic approach for implementing flexible electric energy systems in smart cities. The SE-OS methodologies are based on methods for data analytics, cyber physical modelling, forecasting, control, optimization, IoT, IoS, and cloud computing. The SE-OS concept has being used for enabling flexibility and demand response in smart cities in a large number of demo project. Finally it is shown that SE-OS in combination with methods for energy systems (gas, thermal, power, biomass, fuel) integration can provide virtual energy storage solutions on all relevant time scales, ie. from minutes to seasonal storage.

The Smart-Energy Operating-System (SE-OS) is used to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for operating flexible electrical energy systems at all scales.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science , Dynamical Systems
Contributors: Madsen, H., Parvizi, J., Bacher, P.
Number of pages: 1
Publication date: 2016
Peer-reviewed: Yes
URLs:
http://www.sustain.dtu.dk/

Bibliographical note
Sustain Abstract L-1
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2016

Characterising the Actual Thermal Performance of Buildings: Current Results of Common Exercises Performed in the Framework of the IEA EBC Annex 58-Project

Several studies have shown that actual thermal performance of buildings after construction may deviate significantly from that anticipated at design stage. As a result, there is growing interest in full scale testing of components and whole buildings. The IEA EBC Annex 58-project ‘Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements’ is developing the necessary knowledge and tools to achieve reliable in-situ dynamic testing and
data analysis methods that can be used to characterise the actual thermal performance and energy efficiency of building components and whole buildings. The research within this project is driven by case studies. As a first simple case, an experiment on testing and data analysis is performed on a round robin test box. This test box can be seen as a scale model of a building, built by one of the participants, with fabric properties unknown to all other participants. Full scale measurements have been performed on the test box in different countries under real climatic conditions. The obtained dynamic data are distributed to all participants who have to try to characterise the thermal performance of the test box's fabric based on the provided data.

This paper presents the first results obtained on the round robin experiment. It is shown how different techniques can be used to characterise the thermal performance of the test box, ranging from a simple stationary analysis to advanced dynamic data analysis methods.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, KU Leuven
Contributors: Roels, S., Bacher, P., Bauwens, G., Madsen, H., Jiménez, M. J.
Pages: 3282-3287
Publication date: 2015
Peer-reviewed: Yes

Publication information
Journal: Energy Procedia
Volume: 78
Issue number: November
ISSN (Print): 1876-6102
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 1.44 SJR 0.495 SNIP 0.799
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.16 SJR 0.464 SNIP 0.598
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 0.92 SJR 0.359 SNIP 0.562
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 1.09 SJR 0.429 SNIP 0.807
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 1.02 SJR 0.42 SNIP 0.778
ISI indexed (2013): ISI indexed no
Web of Science (2013): Indexed yes
Scopus rating (2012): CiteScore 1.08 SJR 0.411 SNIP 0.55
ISI indexed (2012): ISI indexed no
Web of Science (2012): Indexed yes
Scopus rating (2011): CiteScore 2.42 SJR 0.877 SNIP 1.45
ISI indexed (2011): ISI indexed no
Scopus rating (2010): SJR 0.416 SNIP 0.91
Web of Science (2009): Indexed yes
Original language: English
Electronic versions:
1_s2.0_S1876610215024583_main.pdf
DOIs:
10.1016/j.egypro.2015.11.726
Source: PublicationPreSubmission
Source-ID: 119412420
Research output: Research - peer-review › Conference article – Annual report year: 2015
Integrated energy systems modelling

General information
State: Published
Organisations: Department of Management Engineering, Systems Analysis, Energy Systems Analysis, Department of Applied Mathematics and Computer Science, Dynamical Systems
Contributors: Karlsson, K., Skytte, K., Morthorst, P. E., Bacher, P., Madsen, H.
Pages: 23-33
Publication date: 2015

Host publication information
Title of host publication: DTU International Energy Report 2015: Energy systems integration for the transition to non-fossil energy systems
Publisher: Technical University of Denmark (DTU)
Editors: Hvidtfeldt Larsen, H., Sønderberg Petersen, L.
ISBN (Print): 978-87-550-3970-4
Electronic versions:
Research output: Research - peer-review › Book chapter – Annual report year: 2015

Introduction to Statistics - eNotes
Online textbook used in the introductory statistics courses at DTU. It provides a basic introduction to applied statistics for engineers. The necessary elements from probability theory are introduced (stochastic variable, density and distribution function, mean and variance, etc.) and thereafter the most basic statistical analysis methods are presented: Confidence band, hypothesis testing, simulation, simple and multiple regression, ANOVA and analysis of contingency tables. Examples with the software R are included for all presented theory and methods.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Statistics and Data Analysis, Dynamical Systems
Contributors: Brockhoff, P. B., Møller, J. K., Andersen, E. W., Bacher, P., Christiansen, L. E.
Publication date: 2015

Publication information
Year: 2015
Original language: English
URLs:
http://introstat.compute.dtu.dk/enote/
Research output: Education › Net publication - Internet publication – Annual report year: 2015

Methodology and forecast products for the optimal offering of ancillary services from wind in a market environment
In this report models for extreme negative wind power forecast errors are presented. The models can be applied to estimate levels below which the wind power rarely drops. Such levels could be called "certain-levels" or "guaranteed levels" of wind power, well knowing that full guarantee never can be given. The estimated levels are obtained by modelling the error from already existing wind power forecasting software, this is accomplished by modelling the residuals with statistical extreme value techniques.

The forecasts can be used in the operation of power systems with significant amounts of wind power for example in the planning of ancillary power services, where the level of available wind power with a high degree of certainty is important to know.

The presented extreme value models are applied to negative forecast residuals from state-of-the-art wind power forecast software. This enables the estimation of return levels below which the extreme wind power forecast error events occur only at a specified rate, e.g. once a month or once every year. The techniques allows extrapolation beyond the available data period. In the study data from 1.5 years is used. It consists of hourly wind power production in the two regions of Denmark (DK1 and DK2) and corresponding wind power forecasts. The wind power forecasts are generated using the software WPPT and are based on the outcome of three numerical weather prediction models. They cover horizons from 1 to 42 hours in time and are updated each hour.

In the report a range of extreme value models are suggested. They are of increasing complexity and a model selection is carried using statistical measures and test. A normal procedure when building forecasting models is to divide the data into a learning and a test set to cross-validate the results in order to avoid over-fitting the models. This is hardly ever possible for extreme value analysis, instead the model selection and evaluation sole rely on statistical techniques such as correlation measures, likelihood ratio-tests and information about uncertainty, for example in the form of confidence bands.
on parameter estimates and predictions.

The foundation to statistical extreme value theory was set by Fisher and Tippett in 1928 and later developed by Gumbel (1958). Since then it has been used for modelling extremes in a wide range of applications. Typical applications are for estimation of extreme weather induced phenomena, for example extreme water levels in a river, wind levels or at sea for design of dykes (de Haan and de Ronde, 1998). In insurance and finance the extreme value modelling is widespread (Embrechts et al., 1997). Extreme value statistics for energy and power applications is also widely used, for example for planning in wind power operation (Horvat et al., 2013) and peak wind prediction (Cook, 1982) and (Friederichs and Thorarinsdottir, 2012). Several books provide comprehensive introductions to extreme value theory, for example Coles (2001) and Beirlant et al. (2006). A really good overview of available extreme value analysis software is given by (Stephenson and Gilleland, 2005). In the present study the R R Core Team (2013) package extRemes Gilleland and Katz (2011) is used.

Thermal Performance Characterization using Time Series Data - IEA EBC Annex 58 Guidelines

This document presents guidelines for using time series analysis methods, models and tools for estimating the thermal performance of buildings and building components. The thermal performance is measured as estimated parameters of a model, or parameters derived from estimated parameters of a model. A special focus will be on estimating the Heat Loss Coefficient (HLC) and gA-value. Provided in the guidelines are modelling procedures with which consistent results for estimation of energy performance of buildings and building components can be achieved.

These guidelines start with simple (non-dynamical) steady state models where the parameters are found using classical methods for linear regression. Such steady state techniques provide sub-optimal use of the information embedded in the data and provides information only about the HLC and gA-values.

Next the guidelines consider dynamical models. Firstly, linear input-output models are considered. More specifically we will consider the class of AutoRegressive with eXogenous input (ARX) (p) models. These models provides information about the HLC and gA-values, and information about the dynamics (most frequently described as time-constants for the system).

Finally, grey-box models are considered. This class of models is formulated as state space models which are able to provide rather detailed information about the internal physical parameters of a construction. This class of models bridges the gap between physical and statistical modelling. A grey-box model is formulated as a continuous time model for the states of the system, together with a discrete set of equations describing how the measurements are linked to the states. The frequently used so-called RC-network models belongs to the class of linear greybox models. However, advanced constructions, like a wall with PV-integration or a complex building with a lot of glass, often calls for a description of nonlinear phenomena. This can be facilitated by the class of non-linear grey-box models.

It is assumed that data is available as time series of measurements. Hence it should be noticed that the important steps of experimental design and setting up the experiment have been conducted.
IEA Common Exercise 4: ARX, ARMAX and grey-box models for thermal performance characterization of the test box

In this report results of applying time series models for assessing the thermal performance of the IEA Annex 58 test box based on data given in the Common Exercise 4 (CE4), which was measured in Almeria, Spain. Both ARX, ARMAX and grey-box models are applied. Finally, the same models are fitted for the Common Exercise 3b (CE3) data measured in Belgium and the results are compared.

The focus in this report is on model selection and validation enabling a stable and reliable performance assessment. Basically, the challenge is to find a procedure for each type of model, which can give un-biased and accurate estimates of the essential performance parameters, including reliable uncertainties of the estimates. Important is also the development of methodologies for analyzing the quality of data, for example correlated inputs and lack of information in data (e.g. if no clearsky days with direct solar radiation is present data), these aspects are discussed. Furthermore, new models for enhancing the description of the effect of solar radiation on the test box is presented.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems
Contributors: Bacher, P., Andersen, P. H. D.
Number of pages: 49
Publication date: 2014

Setting up and validating a complex model for a simple homogeneous wall

The present paper describes modelling of the thermal dynamics of a real wall tested in dynamic outdoor weather conditions, to identify all the parameters needed for its characterisation. Specifically, the U value, absorptance and effective heat capacity are estimated for the wall using grey-box modelling based on statistical methods and known physical dynamic energy balance equations, related to the heat flux density through a simple and homogeneous wall. The experimental test was carried out in a hot-temperature climate for nine months. This study aims at proposing a dynamic method improving the regression averages method for estimation of parameters which describe the thermal behaviour of the wall. Solar irradiance and long-wave radiation balance terms are added in the heat balance equation besides modelling of wind speed effect to achieve a complete description of the relevant phenomena which affect the thermal dynamics of the wall. The method is applied using different frequency data samples looking for the best to study this wall. The U value obtained characterising the wall is consistent with the one given by the regression averages method.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Centro de Investigaciones Energéticas, MedioAmbientales y Tecnológicas, University of Granada
Contributors: Naveros, I., Bacher, P., Ruiz, D. P., Jiménez, M. J., Madsen, H.
Pages: 303-317
Publication date: 2014
Peer-reviewed: Yes
A non-parametric method for correction of global radiation observations

This paper presents a method for correction and alignment of global radiation observations based on information obtained from calculated global radiation, in the present study one-hour forecast of global radiation from a numerical weather prediction (NWP) model is used. Systematical errors detected in the observations are corrected. These are errors such as: tilt in the leveling of the sensor, shadowing from surrounding objects, clipping and saturation in the signal processing, and errors from dirt and wear. The method is based on a statistical non-parametric clear-sky model which is applied to both the observed and the calculated radiation in order to find systematic deviations between them. The method is applied to correct global radiation observations from a climate station located at a district heating plant in Denmark. The results are compared to observations recorded at the Danish Technical University. The method can be useful for optimized use of solar radiation observations for forecasting, monitoring, and modeling of energy production and load which are affected by solar radiation.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Department of Civil Engineering, Section for Building Physics and Services
Contributors: Bacher, P., Madsen, H., Perers, B., Nielsen, H. A.
Pages: 13-22
Publication date: 2013
Peer-reviewed: Yes

Publication information
Journal: Solar Energy
Volume: 88
ISSN (Print): 0038-092X
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 4.89 SJR 1.615 SNIP 1.791
Web of Science (2017): Impact factor 4.374
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.52 SJR 1.504 SNIP 1.746
Web of Science (2016): Impact factor 4.018
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 4.61 SJR 1.912 SNIP 2.085
Web of Science (2015): Impact factor 3.685
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 4.77 SJR 1.962 SNIP 2.671
Web of Science (2014): Impact factor 3.469
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 4.44 SJR 1.99 SNIP 2.85
Web of Science (2013): Impact factor 3.541
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 3.65 SJR 1.605 SNIP 2.517
Web of Science (2012): Impact factor 2.952
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 3.19 SJR 1.283 SNIP 2.178
Web of Science (2011): Impact factor 2.475
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.369 SNIP 2.16
Web of Science (2010): Impact factor 2.172
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.265 SNIP 2.158
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.684 SNIP 1.994
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.685 SNIP 2.085
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.594 SNIP 2.229
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 1.233 SNIP 1.601
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.523 SNIP 1.702
Scopus rating (2003): SJR 1.152 SNIP 1.423
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 1.331 SNIP 1.561
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 1.292 SNIP 1.277
Scopus rating (2000): SJR 0.77 SNIP 1.065
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 0.688 SNIP 1.253

Original language: English
Keywords: Global solar radiation, Observations, Correction, Quality control, Statistical clear-sky model, Solar energy
Electronic versions:
correctionpaper.pdf
DOIs:
10.1016/j.solener.2012.10.024
Source: dtu
Source-ID: n::oai:DTIC-ART:compendex/377168793::24505
Grey-box Modeling for System Identification of Household Refrigerators: a Step Toward Smart Appliances

This paper presents the grey-box modeling of a vapor-compression refrigeration system for residential applications based on maximum likelihood estimation of parameters in stochastic differential equations. Models obtained are useful in the view of controlling refrigerators as flexible consumption units, which operation can be shifted within temperature and operational constraints. Even if the refrigerators are not intended to be used as smart loads, validated models are useful in predicting units consumption. This information can increase the optimality of the management of other flexible units, such as heat pumps for space heating, in order to smooth the load factor during peak hours, enhance reliability and efficiency in power networks and reduce operational costs.

General information
State: Published
Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Department of Applied Mathematics and Computer Science, Dynamical Systems
Contributors: Costanzo, G. T., Sossan, F., Marinelli, M., Bacher, P., Madsen, H.
Number of pages: 5
Publication date: 2013

Host publication information
Title of host publication: Proceedings of IEEE 4th International Youth Conference on Energy
Publisher: IEEE
Keywords: Refrigerators, Stochastic processes, System identification, Load shifting
Electronic versions: bare_jrnl.pdf
DOIs: 10.1109/IYCE.2013.6604197
Source: dtu
Source-ID: u::8573
Research output: Research - peer-review › Article in proceedings – Annual report year: 2013

Load forecasting for supermarket refrigeration

This report presents a study of models for forecasting the load for supermarket refrigeration. The data used for building the forecasting models consists of load measurements, local climate measurements and weather forecasts. The load measurements are from a supermarket located in a village in Denmark. The load for refrigeration is the sum of all cabinets in the supermarket, both low and medium temperature cabinets, and spans a period of one year. As input to the forecasting models the ambient temperature observed near the supermarket together with weather forecasts are used. Every hour the hourly load for refrigeration for the following 42 hours is forecasted. The forecast models are adaptive linear time-series models which are fitted with a computationally efficient recursive least squares scheme. The dynamic relations between the inputs and the load is modeled by simple transfer functions. The system operates in two regimes: one in the closing hours during night and one in the opening hours during the day. This is modeled by a regime switching model in which some of the coefficients in the model depends on the regime. The results show that the one-step ahead residuals are close to white noise, however some dependence on the ambient temperature remains, which is caused by non-linearities in the relation between the load and the ambient temperature. Suggestions for including these non-linearities are given in the discussion of the results.

The report starts with a section in which the data and the NWPs are described. This is followed by a presentation of the modeling approach and the model identification, where a suitable forecasting model is found. Finally, the results are presented, and the method is discussed and conclusions are drawn.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, ENFOR A/S
Contributors: Bacher, P., Madsen, H., Aalborg Nielsen, H.
Number of pages: 25
Publication date: 2013

Publication information
Publisher: DTU Compute
Original language: English
Electronic versions: tr13_08_2ed_Bacher_P.pdf
Research output: Research › Report – Annual report year: 2013
Online load forecasting for supermarket refrigeration
This paper presents a study of models for forecasting the load for supermarket refrigeration. The data used for building the forecasting models consists of load measurements, local climate measurements and weather forecasts. The load measurements are from a supermarket located in a village in Denmark. Every hour the hourly load for refrigeration for the following 42 hours is forecasted. The forecast models are time adaptive linear time-series models. The dynamic relations between the inputs and the load is modeled by simple transfer functions. The system operates in two regimes: one in the closing hours during night and one in the opening hours during the day. This is modeled by a regime switching model in which some of the coefficients in the model depends on the regime. The results show that the one-step ahead residuals are close to white noise, however it is found that some non-linear dependence on the ambient temperature should be included in the model in further work.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science , Dynamical Systems
Contributors: Bacher, P., Madsen, H., Nielsen, H. A.
Number of pages: 5
Publication date: 2013

Host publication information
Title of host publication: 2013 4th IEEE/PES Innovative Smart Grid Technologies Europe (ISGT EUROPE)
Publisher: IEEE
Article number: 6695467
ISBN (Print): 978-1-4799-2984-9
DOIs: 10.1109/ISGTEurope.2013.6695467
Source: dtu
Source-ID: n::oai:DTIC-ART:iel/429864712::36936
Research output: Research - peer-review › Article in proceedings – Annual report year: 2013

Online short-term heat load forecasting for single family houses
This paper presents a method for forecasting the load for heating in a single-family house. Both space and hot tap water heating are forecasted. The forecasting model is built using data from sixteen houses in Sønderborg, Denmark, combined with local climate measurements and weather forecasts. Every hour the hourly heat load for each house the following two days is forecasted. The forecast models are adaptive linear time-series models and the climate inputs used are: ambient temperature, global radiation, and wind speed. A computationally efficient recursive least squares scheme is used. The models are optimized to fit the level of optimal adaptivity and the thermal dynamical response of the building. Identification of a model, which is suitable for application to all the houses, is carried out. The results show that the forecasting errors mainly are related to: unpredictable high frequency variations in the heat load signal (predominant only for some houses), peaks presumably from showers, shifts in resident behavior, and uncertainty of the weather forecasts for longer horizons, especially for the solar radiation.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science , Dynamical Systems
Contributors: Bacher, P., Madsen, H., Nielsen, H. A.
Pages: 5741-5746
Publication date: 2013

Host publication information
Title of host publication: 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013
Publisher: IEEE
DOIs: 10.1109/IECON.2013.6700075
Source: dtu
Source-ID: n::oai:DTIC-ART:iel/429865573::38853
Research output: Research - peer-review › Article in proceedings – Annual report year: 2013

Short-term heat load forecasting for single family houses
This paper presents a method for forecasting the load for space heating in a single-family house. The forecasting model is built using data from sixteen houses located in Sønderborg, Denmark, combined with local climate measurements and weather forecasts. Every hour the hourly heat load for each house the following two days is forecasted. The forecast models are adaptive linear time-series models and the climate inputs used are: ambient temperature, global radiation and wind speed. A computationally efficient recursive least squares scheme is used. The models are optimized to fit the
individual characteristics for each house, such as the level of adaptivity and the thermal dynamical response of the building, which is modeled with simple transfer functions. Identification of a model, which is suitable for all the houses, is carried out. The results show that the one-step ahead errors are close to white noise and that practically all correlation to the climate variables are removed. Furthermore, the results show that the forecasting errors mainly are related to: unpredictable high frequency variations in the heat load signal (predominant only for some houses), shifts in resident behavior patterns and uncertainty of the weather forecasts for longer horizons, especially for solar radiation.

**General information**

State: Published  
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Department of Civil Engineering, Section for Building Physics and Services  
Contributors: Bacher, P., Madsen, H., Nielsen, H. A., Perers, B.  
Pages: 101-112  
Publication date: 2013  
Peer-reviewed: Yes

**Publication information**

Journal: Energy and Buildings  
Volume: 65  
ISSN (Print): 0378-7788  
Ratings:  
BFI (2019): BFI-level 2  
Web of Science (2019): Indexed yes  
BFI (2018): BFI-level 2  
Web of Science (2018): Indexed yes  
BFI (2017): BFI-level 2  
Scopus rating (2017): CiteScore 4.96 SJR 2.061 SNIP 2.12  
Web of Science (2017): Impact factor 4.57  
Web of Science (2017): Indexed yes  
BFI (2016): BFI-level 2  
Scopus rating (2016): CiteScore 4.64 SJR 2.055 SNIP 1.968  
Web of Science (2016): Impact factor 4.67  
Web of Science (2016): Indexed yes  
BFI (2015): BFI-level 2  
Scopus rating (2015): CiteScore 4.07 SJR 2.04 SNIP 2.146  
Web of Science (2015): Impact factor 2.973  
Web of Science (2015): Indexed yes  
BFI (2014): BFI-level 2  
Scopus rating (2014): CiteScore 4.21 SJR 2.079 SNIP 2.875  
Web of Science (2014): Impact factor 2.884  
Web of Science (2014): Indexed yes  
BFI (2013): BFI-level 2  
Scopus rating (2013): CiteScore 3.79 SJR 1.852 SNIP 2.404  
Web of Science (2013): Impact factor 2.65  
ISI indexed (2013): ISI indexed yes  
Web of Science (2013): Indexed yes  
BFI (2012): BFI-level 2  
Scopus rating (2012): CiteScore 3.36 SJR 1.745 SNIP 2.696  
Web of Science (2012): Impact factor 2.679  
ISI indexed (2012): ISI indexed yes  
Web of Science (2012): Indexed yes  
BFI (2011): BFI-level 2  
Scopus rating (2011): CiteScore 3.23 SJR 1.476 SNIP 2.531  
Web of Science (2011): Impact factor 2.386  
ISI indexed (2011): ISI indexed yes  
Web of Science (2011): Indexed yes  
BFI (2010): BFI-level 2
Solar/electric heating systems for the future energy system

The project “Solar/electric heating systems in the future energy system” was carried out in the period 2008-2013. The project partners were DTU Byg, DTU Informatics (now DTU Compute), DMI, ENFOR A/S and COWI A/S. The companies Ajva ApS, Ohmatex ApS and Innogie ApS worked together with the project partners in two connected projects in order to develop solar/electric heating systems for laboratory tests. The project was financed by the Danish Agency for Science, Technology and Innovation under the Danish Council for Strategic Research in the program Sustainable Energy and Environment. The DSF number of the project is 2104-07-0021/09-063201/DSF. This report is the final report of the project. The aim of the project is to elucidate how individual heating units for single family houses are best designed in order to fit into the future energy system. The units are based on solar energy, electrical heating elements/heat pump, advanced heat storage tanks and advanced control systems.

Heat is produced by solar collectors in sunny periods and by electrical heating elements/heat pump. The electrical heating elements/heat pump will be in operation in periods where the heat demand cannot be covered by solar energy. The aim is to use the auxiliary heating units when the electricity price is low, e.g. due to large electricity production by wind turbines.

The unit is equipped with an advanced control system where the control of the auxiliary heating is based on forecasts of the electricity price, the heat demand and the solar energy production. Consequently, the control is based on weather forecasts.

Three differently designed heating units are tested in a laboratory test facility. The systems are compared on the basis of:
- energy consumption for the auxiliary heating
- energy cost for the auxiliary heating
- net utilized solar energy
An improved dynamic test method for solar collectors

A comprehensive improvement of the mathematical model for the so-called transfer function method is presented in this study. This improved transfer function method can estimate the traditional solar collector parameters such as zero loss coefficient and heat loss coefficient. Two new collector parameters $t$ and $m$ are obtained. $t$ is a time scale parameter which can indicate the heat transfer ability of the solar collector. $m$ can be used to calculate the fluid volume content in the solar collector or to validate the regression process by comparing it to the physical fluid volume content if known. Experiments were carried out under dynamic test conditions and then test data were processed using multi-linear regression method to get collector parameters with statistic analysis. A comparison of the collector parameters obtained from the improved transfer function (ITF) method and the quasi-dynamic test (QDT) method is carried out. The results show that the improved transfer function method can accurately obtain reasonable collector parameters. The influence of different averaging time intervals is investigated. Based on the investigation, it is recommended to use line calculation if applicable for the second-order differential term with 6–9min as the best averaging time interval. The measured and predicted collector power output of the solar collector are compared during a test of 13days continuously both for the ITF method and the QDT method. The maximum and averaging error is 53.87W/m² and 5.22W/m² respectively of the ITF method while 64.13W/m² and 6.22W/m² of the QDT method. Scatter and relative error distribution of the measured power output versus the predicted power output is also plotted for the two methods. No matter in either error analysis or scatter distribution, the ITF method is more accurate than the QDT method in predicting the power output of a solar collector. In conclusion, all the results show that the improved transfer function method can accurately and robustly estimate solar collector parameters and predict solar collector thermal performance under dynamic test conditions.
Load Forecasting for Households

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics, Department of Civil Engineering, Section for Building Physics and Services, ENFOR A/S
Publication date: 2012

Publication information
Publisher: iPower Consortium
Original language: English
Research output: Research - peer-review › Report – Annual report year: 2012

Modelling the heat dynamics of a monitored Test Reference Environment for Building Integrated Photovoltaic systems using stochastic differential equations

This paper deals with grey-box modelling of the energy transfer of a double skin Building Integrated Photovoltaic (BIPV) system. Grey-box models are based on a combination of prior physical knowledge and statistics, which enable identification of the unknown parameters in the system and accurate prediction of the most influential variables. The experimental data originates from tests carried out with an air-based BIPV system installed in a Test Reference Environment. BIPV systems represent an interesting application for achieving the requirements of the EU EPBD Directive. Indeed, these systems could reduce the ventilation thermal losses of the building by pre-heating the fresh air. Furthermore, by decreasing PV module temperature, the ventilation air heat extraction can simultaneously increase electrical and thermal energy production of the building. A correct prediction of the PV module temperature and heat transfer coefficients is fundamental in order to improve the thermo-electrical production. The considered grey-box models are composed of a set of continuous time stochastic differential equations, holding the physical description of the system, combined with a set of discrete time measurement equations, which represent the data driven part. In the present work, both one-state and two-state non-linear grey-box models are considered. In order to validate the results, the residuals are analysed for white-noise properties.

General information
State: Published
Model predictive control for a smart solar tank based on weather and consumption forecasts

In this work the heat dynamics of a storage tank were modelled on the basis of data and maximum likelihood methods. The resulting grey-box model was used for Economic Model Predictive Control (MPC) of the energy in the tank. The control objective was to balance the energy from a solar collector and the heat consumption in a residential house. The storage tank provides heat in periods where there is low solar radiation and stores heat when there is surplus solar heat. The forecasts of consumption patterns were based on data obtained from meters in a group of single-family houses in Denmark. The tank can also be heated by electric heating elements if necessary, but the electricity costs of operating these heating elements should be minimized. Consequently, the heating elements should be used in periods with cheap electricity. It is proposed to integrate a price-sensitive control to enable the storage tank to serve a smart energy system in which flexible consumers are expected to help balance fluctuating renewable energy sources like wind and solar. Through simulations, the impact of applying Economic MPC shows annual electricity cost savings up to 25-30%.

General information
State: Published
Organisations: Center for Energy Resources Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing, Mathematical Statistics, Department of Civil Engineering, Section for Building Physics and Services
Contributors: Halvgaard, R., Bacher, P., Perers, B., Andersen, E., Furbo, S., Jørgensen, J. B., Poulsen, N. K., Madsen, H.
Pages: 270-278
Publication date: 2012
Peer-reviewed: Yes

Publication information
Journal: Energy Procedia
Volume: 30
ISSN (Print): 1876-6102
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 1.44 SJR 0.495 SNIP 0.799
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.16 SJR 0.464 SNIP 0.598
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 0.92 SJR 0.359 SNIP 0.562
Efficient operation of energy systems with substantial amount of renewable energy production is becoming increasingly important. Renewables are dependent on the weather conditions and are therefore by nature volatile and uncontrollable, opposed to traditional energy production based on combustion. The "smart grid" is a broad term for the technology for addressing the challenge of operating the grid with a large share of renewables. The "smart" part is formed by technologies, which models the properties of the systems and efficiently adapt the load to the volatile energy production, by using the available flexibility in the system.

In the present thesis methods related to operation of solar energy systems and for optimal energy use in buildings are presented. Two approaches for forecasting of solar power based on numerical weather predictions (NWPs) are presented, they are applied to forecast the power output from PV and solar thermal collector systems. The first approach is based on a developed statistical clear-sky model, which is used for estimating the clear-sky output solely based on observations of the output. This enables local effects such as shading from trees to be taken into account. The second approach to solar power forecasting is based on conditional parametric modelling. It is well suited for forecasting of solar thermal power, since it can be made non-linear in the inputs. The approach is also extended to a probabilistic solar power forecasting model.

The statistical clear-sky model is furthermore used as basis for a method for correction of global radiation observations. This method can be used for correction of typical errors, for example from shading trees or buildings. Two methods for efficient energy use in buildings are presented in the last part of the thesis. First a method for forecasting of the heat load in single-family houses based on weather forecasts is presented. A model is identified, which works well when applied to forecast the heat load for sixteen single-family houses. The model adapts to the individual houses and needs no specific information about the buildings. Finally a procedure for identification of a suitable model for the heat dynamics of a building is presented. The applied models are greybox model based on stochastic differential equations and the identification is carried out with likelihood ratio tests. The models can be used for providing detailed information of the thermal characteristics of buildings and as basis for optimal control for flexible heating of buildings.
Identifying suitable models for the heat dynamics of buildings

General information
State: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Bacher, P., Madsen, H.
Pages: 1511-1522
Publication date: 2011
Peer-reviewed: Yes

Publication information
Journal: Energy and Buildings
Volume: 43
Issue number: 7
ISSN (Print): 0378-7788
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 4.96 SJR 2.061 SNIP 2.12
Web of Science (2017): Impact factor 4.457
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4.64 SJR 2.055 SNIP 1.968
Web of Science (2016): Impact factor 4.067
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.07 SJR 2.04 SNIP 2.146
Web of Science (2015): Impact factor 2.973
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.21 SJR 2.079 SNIP 2.875
Web of Science (2014): Impact factor 2.884
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.79 SJR 1.852 SNIP 2.404
Web of Science (2013): Impact factor 2.465
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.36 SJR 1.745 SNIP 2.696
Web of Science (2012): Impact factor 2.679
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 3.23 SJR 1.476 SNIP 2.531
Web of Science (2011): Impact factor 2.386
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.626 SNIP 2.08
Web of Science (2010): Impact factor 2.046
Web of Science (2010): Indexed yes
Improved experimental setup for observation of non-linear heat dynamics

Modeling of heat dynamics of houses have been reported successful using linear dynamical models. The room they leave for improvement is because of physical relations believed to be partly caused by non-linear relations. As model complexity increases, detailed measurements and highly modular experiments are gaining importance in estimation of model parameters. This paper describes test facilities and new measurement equipment in a low-energy house in arctic area. Furthermore, some of the models that will be applied are described.

General information
State: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Section for Building Physics and Services, Department of Civil Engineering, ENFOR A/S
Contributors: Andersen, P. H. D., Madsen, H., Bacher, P., Rode, C., Nielsen, H. A.
Publication date: 2011

Host publication information
Title of host publication: Proceedings of the DYNASTEE international workshop
Electronic versions:
pd_paper_dynastee_2011.pdf
Source: orbit
Source-ID: 316149
Research output: Research - peer-review › Article in proceedings – Annual report year: 2011

Models of the heat dynamics of solar collectors for performance testing

The need for fast and accurate performance testing of solar collectors is increasing. This paper describes a new technique for performance testing which is based on non-linear continuous time models of the heat dynamics of the collector. It is shown that all important performance parameters can be accurately estimated with measurements from a single day. The estimated parameters are compared with results from standardized test methods (Fischer et al., 2004). Modelling the dynamics of the collector is carried out using stochastic differential equations, which is a well proven efficient method to
obtain accurate estimates of parameters in physical models. The applied method is described by Kristensen et al. (2004) and implemented in the software CTSM1. Examples of successful applications of the method includes modelling the heat dynamics of integrated photo-voltaic modules (Friling et al., 2009) and modelling of the heat dynamics of buildings (Madsen and Holst, 1995). Measurements obtained at a test site in Denmark during the spring 2010 are used for the modelling. The tested collector is a single glazed large area flat plate collector with selective absorber and Teflon anti convection layer. The test rig is described in Fan et al. (2009). The modelling technique provides uncertainty estimates such as confidence intervals for the parameters, and furthermore enables statistical validation of the results. Such tests can also facilitate procedures for selecting the best model to use, which is a very non-trivial task.

Online Short-term Solar Power Forecasting

This poster presents two approaches to online forecasting of power production from PV systems. The methods are suited for online forecasting in many applications and here they are used to predict hourly values of solar power for horizons up to 32 hours.

General information
State: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Bacher, P., Madsen, H., Nielsen, H. A.
Publication date: 2011
Peer-reviewed: Yes
Electronic versions:
poster.pdf
URLs:
http://www.solarintegrationworkshop.org/
Source: orbit
Source-ID: 312981
Research output: Research - peer-review › Poster – Annual report year: 2011
**Opensource Software for MLR-Modelling of Solar Collectors**

A first research version is now in operation of a software package for multiple linear regression (MLR) modeling and analysis of solar collectors according to ideas originating all the way from Walletun et. al. (1986), Perers, (1987 and 1993). The tool has been implemented in the free and open source program R http://www.r-project.org/. Applications of the software package includes: visual validation, resampling and conversion of data, collector performance testing analysis according to the European Standard EN 12975 (Fischer et al., 2004), statistical validation of results, and the determination of collector incidence angle modifiers without the need of a mathematical function (Perers, 1997). The paper gives a demonstration with examples of the applications, based on measurements obtained at a test site at DTU in Denmark (Fan et al., 2009). The tested collector is a single glazed large area flat plate collector with selective absorber and teflon anti convection layer. The package is intended to enable fast and reliable validation of data, and provide a united implementation for MLR testing of solar collectors. This will furthermore make it simple to replicate the calculations by a third party in order to validate the results. Finally more advanced methods can be implemented and easily shared as extensions to the package, for example methods for statistical estimation of the incidence angle modifier with non-linear functions for collectors with more complicated optics. The overall advantage of this kind of tool and analysis is that it is almost the inverse of simulation. Therefore the model and parameters will be very well validated for application in later use for system simulation, even if the test is no real system test. Also for annual collector performance calculations with a new Excel tool connected to EN 12975 (Kovacs, 2011) this built in validation gives an extra quality assurance.

**General information**

State: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Section for Building Physics and Services, Department of Civil Engineering
Contributors: Bacher, P., Perers, B.
Publication date: 2011

**Host publication information**

Title of host publication: Proceedings of ISES Solar World Conference 2011
Electronic versions:
Bacher2011c.pdf
URLs:
http://www.swc2011.org/cms/
Source: orbit
Source-ID: 312984
Research output: Research - peer-review › Article in proceedings – Annual report year: 2011

**Short-Term Solar Collector Power Forecasting**

This paper describes a new approach to online forecasting of power output from solar thermal collectors. The method is suited for online forecasting in many applications and in this paper it is applied to predict hourly values of power from a standard single glazed large area flat plate collector. The method is applied for horizons of up to 42 hours. Solar heating systems naturally come with a hot water tank, which can be utilized for energy storage also for other energy sources. Thereby such systems can become an important part of energy systems with a large share of uncontrollable energy sources, such as wind power. In such a scenario online forecasting is a vital tool for optimal control and utilization of solar heating systems. The method is a two-step scheme, where first a non-linear model is applied to transform the solar power into a stationary process, which then is forecasted with robust time-adaptive linear models. The approach is similar to the one by Bacher et al. (2009), but contains additional effects due to differences between solar thermal collectors and photovoltaics. Numerical weather predictions provided by Danish Meteorological Institute are used as input. The applied models adapt over time enabling tracking of changes in the system and in the surrounding conditions, such as decreasing performance due to wear and dirt, and seasonal changes such as leaves on trees. This furthermore facilitates remote monitoring and check of the system.

**General information**

State: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Section for Building Physics and Services, Department of Civil Engineering
Contributors: Bacher, P., Madsen, H., Perers, B.
Publication date: 2011

**Host publication information**

Title of host publication: Proceedings of ISES Solar World Conference 2011
Electronic versions:
Bacher2011a.pdf
URLs:
http://www.swc2011.org/cms/
Analysis of energy consumption in single family houses

This article deals with estimation of the thermal characteristics of single family houses based on measurements of energy consumption and climate. The thermal characteristics includes the response of the building to changes in temperature (UA-value), solar radiation (gA-value), and wind (wA-value). The effect of the wind is characterized both in terms of the wind speed and the wind direction, implying that wA-values are estimated for different wind directions. In case only stationary characteristics are of interest it is sufficient to base the estimation on 24 hour averages, whereas in order to estimate the dynamic effects averages with a sample period around 4 hours are required. Also, it is beneficial to use measurements of the total energy consumption (heat and electricity). However, in most cases it results in adequate estimates if only the heat consumption is used as the response variable. Obvious exceptions are cases where e.g. electrical floor heating is used for some periods. The estimated thermal characteristics have been analyzed with respect to background information regarding the households. The information is obtained via questionnaires and via the Danish Building Register (BBR). The significant effects are the ground area of the house, the year of construction, and the number of times per week a wood burning stove is used. Consequently, given information regarding the use of wood burning stoves which consumers share, the estimates can be corrected so that adequate values are obtained even for houses where a wood burning stove is being used. The article includes a short outline of how the methods could be integrated in an interactive service such as “My E-Home” minbolig.elsparefonden.dk.

General information
State: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, ENFOR A/S
Contributors: Nielsen, H. A., Mortensen, S. B., Bacher, P., Madsen, H.
Publication date: 2010

Host publication information
Title of host publication: Dynamic Methods for Building Energy Assessment
Keywords: Buildings, thermal characterization, energy labelling, heat consumption, energy performance, smart meters
URLs:
http://www.dynastee.info/home.php
Source: orbit
Source-ID: 270965
Research output: Research › Article in proceedings – Annual report year: 2010

Data for Energy Performance Analysis: Financed by The Danish Electricity Saving Trust

General information
State: Published
Organisations: Intelligent Energy Systems Programme, Risø National Laboratory for Sustainable Energy, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Thavlov, A., Bacher, P., Madsen, H.
Publication date: 2010

Publication information
Place of publication: Kgs. Lyngby
Publisher: Technical University of Denmark, DTU Informatics, Building 321
Original language: English
Keywords: Intelligent energy systems
Electronic versions:
tr10_01.pdf
Source: orbit
Source-ID: 255361
Research output: Research › Report – Annual report year: 2010

Experiments and Data for Building Energy Performance Analysis: Financed by The Danish Electricity Saving Trust

General information
State: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Bacher, P., Madsen, H.
Publication date: 2010
This paper describes a number of statistical methods and models for describing the thermal characteristics of buildings using frequent readings of heat consumption, ambient air temperature, and other available climate variables. For some of the methods frequent readings of the indoor air temperature are needed or beneficial. The suite of models described consists of nonlinear stochastic models, linear stochastic models, transfer function models, frequency response function models, impulse response models and regression models. The final choice of model depends on the purpose of the modelling, existence of prior physical knowledge, the data and the available statistical software tools. The importance of statistical model validation is discussed, and some simple tools for that purpose are demonstrated. This paper also briefly describes some of the most frequently used software tools for modelling the thermal characteristics of buildings. Many of the stochastic models are developed and tested using data from outdoor testing during a number of EU projects (PASSYS, PASLINK, DAME-BC, ...). These projects have provided the background for new methods for using frequent readings of the energy consumption to an assessment of the energy performance of buildings. Smart meters are now used more and more often. A smart meter facilitates frequent reading of the energy consumption, and together with some local meteorological measurements, which almost always are available, the scene is now set for using the developed methods for time series modelling or system identification. Applying these methods the following can be achieved: Characterization of the energy performance of buildings (including energy labelling), identification of how to improve the thermal performance of the building, and improved control of the energy supply.
**General information**

**State:** Published

**Organisations:** Mathematical Statistics, Department of Informatics and Mathematical Modeling, Department of Civil Engineering, Section for Building Physics and Services, ENFOR A/S

**Contributors:** Andersen, P. H. D., Madsen, H., Bacher, P., Rode, C., Nielsen, H. A.

**Publication date:** 2010

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**Host publication information**

**Title of host publication:** Dynamic Methods for Building Energy Assessment

**Keywords:** Grey-box modeling, heat dynamics

**URLs:**


**Source:** orbit

**Source-ID:** 270945

**Research output:** Research > Article in proceedings – Annual report year: 2010

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**Procedure for identifying models for the heat dynamics of buildings: Financed by The Danish Electricity Saving Trust and Vind i Øresund - Interreg 4A**

This report describes a new method for obtaining detailed information about the heat dynamics of a building using frequent reading of the heat consumption. Such a procedure is considered to be of uttermost importance as a key procedure for using readings from smart meters, which is expected to be installed in almost all buildings in the coming years.

**General information**

**State:** Published

**Organisations:** Mathematical Statistics, Department of Informatics and Mathematical Modeling

**Contributors:** Bacher, P., Madsen, H.

**Publication date:** 2010

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**Publication information**

**Place of publication:** Kgs. Lyngby

**Publisher:** Technical University of Denmark, DTU Informatics, Building 321

**Original language:** English

**(IMM-Technical report-2010-04).**

**Electronic versions:**

tr10_04.pdf

**Source:** orbit

**Source-ID:** 258968

**Research output:** Research - peer-review > Report – Annual report year: 2010

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**Statistical models describing the energy signature of buildings**

Approximately one third of the primary energy production in Denmark is used for heating in buildings. Therefore efforts to accurately describe and improve energy performance of the building mass are very important. For this purpose statistical models describing the energy signature of a building, i.e. the heat dynamics of the building, have been developed. The models can be used to obtain rather detailed knowledge of the energy performance of the building and to optimize the control of the energy consumption for heating, which will be vital in conditions with increasing fluctuation of the energy supply or varying energy prices. The paper will give an overview of statistical methods and applied models based on experiments carried out in FlexHouse, which is an experimental building in SYSLAB, Risø DTU. The models are of different complexity and can provide estimates of physical quantities such as UA-values, time constants of the building, and other parameters related to the heat dynamics. A method for selecting the most appropriate model for a given building is outlined and finally a perspective of the applications is given. Aknowledgements to the Danish Energy Saving Trust and the Interreg IV "Vind i Øresund" project.

**General information**

**State:** Published

**Organisations:** Mathematical Statistics, Department of Informatics and Mathematical Modeling, Intelligent Energy Systems Programme, Risø National Laboratory for Sustainable Energy

**Contributors:** Bacher, P., Madsen, H., Thavlov, A.

**Publication date:** 2010
Online short-term solar power forecasting

This paper describes a new approach to online forecasting of power production from PV systems. The method is suited to online forecasting in many applications and in this paper it is used to predict hourly values of solar power for horizons of up to 36 hours. The data used is fifteen-minute observations of solar power from 21 PV systems located on rooftops in a small village in Denmark. The suggested method is a two-stage method where first a statistical normalization of the solar power is obtained using a clear sky model. The clear sky model is found using statistical smoothing techniques. Then forecasts of the normalized solar power are calculated using adaptive linear time series models. Both autoregressive (AR) and AR with exogenous input (ARX) models are evaluated, where the latter takes numerical weather predictions (NWPs) as input. The results indicate that for forecasts up to two hours ahead the most important input is the available observations of solar power, while for longer horizons NWPs are the most important input. A root mean square error improvement of around 35 % is achieved by the ARX model compared to a proposed reference model.

General information

State: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Bacher, P., Madsen, H., Nielsen, H. A.
Pages: 1772-1783
Publication date: 2009
Peer-reviewed: Yes

Publication information

Journal: Solar Energy
Volume: 83
Issue number: 10
ISSN (Print): 0038-092X
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 4.89 SJR 1.615 SNIP 1.791
Projects:

**Stochastic Differential Equations for Modeling Energy Systems Integration**
Real, J. P., PhD Student, Department of Applied Mathematics and Computer Science  
Madsen, H., Main Supervisor, Department of Applied Mathematics and Computer Science  
Bacher, P., Supervisor, Department of Applied Mathematics and Computer Science  
01/02/2019 → 31/01/2022  
Project: PhD

**Decision support by optimization and simulation of households and SMEs in energy systems**
Lemos Vinasco, J., PhD Student, Department of Applied Mathematics and Computer Science  
Møller, J. K., Main Supervisor, Department of Applied Mathematics and Computer Science  
Bacher, P., Supervisor, Department of Applied Mathematics and Computer Science  
Guericke, D., Supervisor, Department of Applied Mathematics and Computer Science  
Madsen, H., Supervisor, Department of Applied Mathematics and Computer Science  
A. Kirknæs, K., Supervisor  
Spur Hansen, A., Supervisor  
01/01/2019 → 31/12/2021  
Project: PhD

**FLEXCoop: Democratizing energy markets through the introduction of innovative flexibility-based demand response tools and novel business and market models for energy cooperatives**
Azar, A. G., Project Participant, Department of Applied Mathematics and Computer Science, Dynamical Systems  
Relan, R., Project Participant, Department of Applied Mathematics and Computer Science, Dynamical Systems  
Bacher, P., Project Participant, Department of Applied Mathematics and Computer Science, Dynamical Systems  
Madsen, H., Project Participant  
01/10/2017 → 30/09/2019  
Project: Research

**Datadriven models for energy advising leading to behavioural changes in SMEs and residences**
Liisberg, J. A. R., PhD Student, Department of Applied Mathematics and Computer Science  
Møller, J. K., Main Supervisor, Department of Applied Mathematics and Computer Science  
Bacher, P., Supervisor, Department of Applied Mathematics and Computer Science  
Madsen, H., Supervisor, Department of Applied Mathematics and Computer Science  
15/05/2016 → 14/05/2019  
Award relations: Datadriven models for energy advising leading to behavioural changes in SMEs and residences  
Project: PhD

**Models for efficient integration of solar energy**
Bacher, P., PhD Student, Department of Informatics and Mathematical Modeling  
Madsen, H., Main Supervisor, Department of Informatics and Mathematical Modeling  
Nielsen, H. A., Supervisor, Department of Informatics and Mathematical Modeling
Solar/electric heating systems in the future energy system

The two most powerful renewable energy sources are solar and wind energy. It is expected that an increasing part of our electricity consumption in the future will be covered by wind farms. This will result in an increased number of windy periods with a surplus of electricity and thereby a low electricity price. A concept where individual solar heating systems optimised for making use of electricity produced by wind turbines in these periods can facilitate the introduction of wind energy in large scale into the energy system and thereby contribute to increasing the part of our energy consumption covered by renewable energy sources. The heat is produced by the solar heating system and by the electric heating element(s)/heat pump, which, if possible, only should be in operation in periods where the solar heating system cannot fully cover the heat demand and where the electricity price is low, e.g. in windy periods with a high electricity production from wind turbines. The unit is equipped with a smart heat storage (variable auxiliary volume) and a smart control system based on prognosis for the electricity price, the heat demand of the house, the solar heat production of the solar heating system and weather forecasts. The project will elucidate how best to design an individual heating unit for one family houses based on the above principles. It is also elucidated how suitable the heating unit is for the home owner and for our future energy system. Different designs of the heating unit and the control system will be investigated and the most promising solutions tested experimentally. It is expected that the heating unit is more cost efficient than traditional solar heating systems and that it can be an attractive alternative to oil- and natural gas boilers, both from an economy and environmental point of view.

Furbo, S., Project Manager, Department of Civil Engineering, Section for Building Physics and Services
Perers, B., Project Participant, Department of Civil Engineering, Section for Building Physics and Services
Nielsen, E. N. N., Project Participant, Department of Civil Engineering, Section for Building Physics and Services
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Bacher, P., Project Participant, Department of Informatics and Mathematical Modeling

Project ID: 25869
Forskningsrådene - Andre: DKK7,406.24
01/04/2008 → 31/12/2011
Collaborators: ENFOR A/S, AllSun A/S, Danish Meteorological Institute, COWI AS
Award relations: Solar/electric heating systems in the future energy system
Project: Research